PART 1

DESIGN TECHNOLOGIES AND SKILLS

1

DIFFERENCE BETWEEN RF AND DIGITAL CIRCUIT DESIGN

1.1 CONTROVERSY

For many years, there has been continued controversy between digital and RF circuit designers, some of which are given below:

- RF circuit designers emphasize impedance matching, whereas digital circuit designers are indifferent to it.
- RF circuit designers are concerned with frequency response, whereas digital circuit designers are interested in the waveform, or "eye's diagram." In other words, RF circuit designers prefer to work in the frequency domain, whereas digital circuit designers like to work in the time domain.
- As a consequence of the above, in a discussion of the budget for equipment, RF circuit designers like to purchase good network analyzers, whereas digital circuit designers prefer to buy the best oscilloscopes.
- RF circuit designers use the unit of dB_W, whereas digital circuit designers insist on using dB_V.
- Not only are the design methodologies different, so are their respective jargons. Digital circuit designers talk about AC bypass capacitors or DC blocking capacitors, but RF circuit designers rename those as "zero" capacitors.

It almost seems as if they were two different kinds of aliens from different planets. Even in some conferences or publications, these two kinds of "aliens" argue with

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each other. Each tries to prove that their design methodology is superior to the others'. Eventually, nobody is the winner.

Let us outline the main controversies in the following.

1.1.1 Impedance Matching

The phrase "impedance matching" comes out of RF circuit designers' mouths almost everyday. They were told by their supervisors that impedance matching is a "must" skill in circuit design. On the other hand, such terminology is never heard among digital circuit designers. Their supervisors tell them, "ignore that 'foreign language' just focus on the 'eye diagram,' or waveform."

It is not just digital circuit designers who ignore impedance matching. Even some RF circuit designers "discovered" something new in their "advanced" RFIC (RF integrated circuit) design. While it was necessary to take care of impedance matching in RF module design or in RF blocks built by discrete parts, where the incident and reflected power in the circuit really existed, they thought it unnecessary to take care of impedance matching in an RFIC circuit design because the size of an IC die is so small as to render distinguishing the incident and reflective power or voltage redundant or meaningless. In agreement with their assertions, in the IC realm the design methodology for the RF circuit should be more or less the same as that for the digital circuit. Since then, they have been designing RF circuit blocks with the same method as used for digital circuit blocks. All the individual RF blocks are simply crowded together since "impedance matching between the individual blocks is not necessary." Their design methodology for RF blocks is specially named as the "Combo" or "Jumbo" design. Theoretically, they thought that all kinds of circuitry must obey Ohm's law and follow KCL (Kirchhoff's current law) and KVL (Kirchhoff's voltage law) rules without exception. So, why is the difference of design methodology? From their viewpoint, it seems unnecessary to divide the circuit design team into an RF and a digital circuit design group accordingly.

RF circuit designers would be very happy if impedance matching was unnecessary because impedance matching is the most difficult task in RF circuit design, especially in RFIC design for the UWB (ultrawide-band) system. Unfortunately, design experience indicates that the Combo or Jumbo design philosophy is absolutely wrong. For instance, without impedance matching, a LNA (low-noise amplifier) becomes a noisy attenuator or an oscillator in an RFIC chip. Without impedance matching, a mixer would become a "real" mixer indeed, blending all desired signals and undesired interference or noise together!

The key point to stop the controversy is whether the concept of voltage or power reflection is available in RF or digital circuitry. Should the reflection of voltage or power not exist in a practical circuitry, the idea of a Combo or Jumbo design could be a correct design methodology. On the contrary, if the reflection of voltage or power exists in a practical circuitry, impedance matching would be important for power transportation or manipulation in a circuitry, and then the idea of Combo or Jumbo design would be an incorrect design methodology.

As a matter of fact, the existence of power or voltage reflection can be deduced from a rough analysis of an RF block. For example, without impedance matching, the insertion loss of an LC passive filter could be significant. However, if the Q values of the inductors or capacitors are high, the LC passive filter itself should not conceivably produce a loss of power. This significant insertion loss demonstrates that quite a lot of power is reflected from the filter or load to the source. On the other hand, power or voltage reflection is not related to the size of the block but to the impedance matching status between the source and the load. A simple example could illustrate the validity of such an assertion: light is reflected from a mirror in the same way no matter whether the light source is far from or very close to the mirror.

1.1.2 Key Parameter

There is a true story from a start-up company researching and developing a wireless communication system.

In spite of different opinions and various comments among his engineering teams, the engineering director asked both his RF and digital circuit design teams to work together for the system design of a communication system. He ruled that *voltage* must be taken as the key parameter to measure the performance of every block, including digital and RF blocks. In other words, the goal of the input and the output in every block, no matter RF or digital, must be specified with the voltage value. This engineering director hates the RF circuit designers' incessant "gossip" about power and impedance.

The engineers did try very hard to follow his instructions. There seemed to be no problem for the digital circuit blocks. However, the engineers were confused and did not know how to specify the goals for RF blocks by voltage instead of power.

By the RF engineers' understanding, all the parameters including G (power gain), NF (noise figure), IP_3 (3rd order intercept point), and IP_2 (2nd order intercept point) applied in RF circuit design were expressed by power but not voltage. In order to follow the director's instructions, they spent a lot of time to convert all the parameters from power to voltage, since power was the traditional unit and was read by most equipment. Sometimes, the conversion was meaningless or uncertain. For instance, by the unit of voltage, CNR (carrier-to-noise ratio) at the input of the demodulator was significantly dependent on the output impedance of the stage before the demodulator and the input impedance of the demodulator. Especially when the output impedance of the stage before the demodulator and the input impedance of the demodulator were different from each other, the conversion becomes impossible. Even more awkwardly, members of audience who attended the presentation meeting held by this system design team could not understand why the values appearing in the system plan were surprisingly higher or lower than those from other companies. Eventually, after they learnt of the extraordinary instructions given by the engineering director, the part of the audience equipped with calculators at hand could not but convert those values back from voltage to power!

Among this system design team, selection of a common key parameter for both RF and digital circuit designs became a hot topic. People argued with each other without result, while the director still insisted on his original instructions. After a couple of weeks, the system design still hung in the air and, finally, for unknown reasons the plan for the system design was dropped quietly. Some RF circuit designers felt upset and left the company despite the director's exhortations: "Nothing is Impossible!"

As a matter of fact, system design for a communication system must be divided into two portions: the digital portion and the RF portion. Yes, the key parameter in the digital circuit design is voltage or current. By means of voltage or current, all the intermediate parameters can be characterized. However, the key parameter in RF circuit design must be power or impedance. By means of power and impedance, all the intermediate parameters in a RF circuit block can be characterized. Impedance matching ensures the best performance of power transportation or manipulation in RF circuit blocks; therefore, impedance can be taken as the key parameter in RF circuit design.

Why? The answer can be found in the following sections.

1.1.3 Circuit Testing and Main Test Equipment

In addition to the arguments about impedance matching and the key parameters, the difference between digital and RF circuit design can also be found in circuit testing and test equipment.

In a digital test laboratory, the test objective is always voltage, and occasionally current. There are many pieces of test equipment available in a digital test laboratory; however, the main test equipment is the oscilloscope. The oscilloscope can sense the voltage at any node in the circuitry and display its eye diagram or a waveform on screen, which characterizes the performance of a digital circuit intuitionally. In general, digital circuit designers prefer to analyze the circuitry in the time domain because the speed of response is important to the performance of a digital circuit block.

In an RF test laboratory, the test objective is always power. Most RF test equipment, such as the spectrum analyzer, noise meter, signal generator, and so on, measure the parameters of an RF circuit block in terms of power but not voltage. The main test equipment is the network analyzer. The performance of an RF circuit block can be characterized mainly by its frequency response on network analyzer screen, which is expressed by power gain or loss, in decibels. The RF circuit designer prefers to analyze the circuitry in the frequency domain because coverage of bandwidth is important to the performance of an RF block.

In the test laboratory, testing a digital circuit block is somewhat easier than testing an RF circuit block. In testing for a digital circuit block, the probe of an oscilloscope is usually a sensor with high impedance. It does not disturb the circuit performance when it touches a node in the circuitry.

On the other hand, while using a network analyzer, the circuit designers may worry about the difference of circuit performance before and after the tested equipment is connected to the desired test node, because the input and output impedance of the equipment is low, usually 50 Ω. In most cases, it certainly will disturb the circuit performance.

Instead of voltage testing, the RF circuit designer is concerned with power testing. All power testing must be conducted under a good impedance matching condition so the test equipment must be well calibrated. Unlike the testing for a digital circuit block by an oscilloscope, a buffer connected between the desired test node and the input of the network analyzer is not allowed because all the power tests for the RF block must be conducted under the condition of impedance matching.

So far, the different methodology between RF and digital circuit design has been introduced only in terms of the three main aspects above. More differences exist but will not be listed. We are going to focus on the explanation of where these differences come from.

1.2 DIFFERENCE OF RF AND DIGITAL BLOCK IN A COMMUNICATION SYSTEM

1.2.1 Impedance

The input and output impedance of an RF circuitry are usually pretty low. In most cases, they are typically 50 Ω. On the contrary, the input and output impedances in a digital circuitry are usually quite high. For example, the input and output impedances of an Op-Amp (operating amplifier) are mostly higher than 10 kΩ.

The lower impedance in an RF circuitry is beneficial to deliver power to a block or a part. It is well known that the power of a signal delivered to a block or a part with impedance Z can be expressed by

$$P = vi = \frac{v^2}{Z}, \tag{1.1}$$

where

$P =$ the power delivered to a block or a part,
$v =$ the AC or RF voltage across the block or the part,
$i =$ the AC or RF current flowing through the block or part, and
$Z =$ the impedance of the block or the part.

For a given value of power, v^2 is proportional to Z. This implies that, in order to deliver a given power to a block or a part, a higher voltage must be provided if its impedance is high. On the contrary, a lower voltage across the block is enough to deliver the same given power to a block or a part if its impedance is low. From the viewpoint of either cost or engineering design of the circuit, the application of a lower voltage is much better than that of a higher voltage. It is one of the reasons why the input and output impedance in the RF blocks are intentionally assigned to be low because only a lower voltage is needed in order to deliver the same given power to a block or part with low impedance.

However, it is just the opposite for a digital signal. The higher impedance in digital circuitry is beneficial to the voltage swing in a digital block or part. For a given current, a higher impedance can have a higher voltage swing across a block or a part, and then the signal can ON/OFF the device more effectively, because

$$v = iZ. \tag{1.2}$$

The question is: why is RF circuitry focused on the power while digital circuitry is concerned about voltage?

1.2.2 Current Drain

In RF circuit blocks, the current drains are usually in the order of milliamperes while in digital circuit blocks they are usually in the order of microamperes. That is, the difference of the current drain's magnitude between RF and digital circuit blocks is approximately 1000 times.

In RF circuit blocks, it is desirable to increase the power of the RF signal as much as possible. This implies that higher current drains are preferred in RF circuit blocks because they are beneficial to deliver power to the block or the part for a given voltage.

In digital circuit blocks, it is desirable to reduce the power of the digital signal as much as possible. This implies that lower current drains are preferred in digital circuit blocks as long as the voltage swing is high enough.

Again, the question is: why is RF circuitry focused on power while digital circuitry is concerned with voltage? The answer can be found in the following section.

1.2.3 Location

In a communication system, the demodulator is a remarkable demarcation in the receiver. As shown in Figure1.1, before the demodulator, the blocks operate in the range of radio frequency so that they are called *RF blocks*. They are sometimes called the *RF front end* in the receiver, where the RF circuit design is conducted. After demodulation, the blocks operate in the range of intermediate frequency or in the low digital data rate and are categorized as baseband blocks, or the digital/analog section. They are sometimes called the *back end* in the receiver, where digital/analog circuit design is conducted. The demodulator is a critical block in which both digital and RF design technology are needed.

The order of blocks in the transmitter is just opposite. Before the modulator, the blocks operate in the range of intermediate frequency or in the low digital data rate and are categorized as baseband blocks, or the digital/analog section. They are sometimes called the *front end* in the transmitter, where digital/analog circuit design is conducted. After the modulator, the blocks operate in the range of radio frequency so that they are called *RF blocks* and sometimes the *RF back end* in the transmitter, where RF circuit design is conducted. The modulator is also a critical block, in which both digital and RF design technology are needed.

A common feature can be seen from Figure 1.1. In either the receiver or the transmitter, the circuit portion close to the antenna side contains RF blocks and the portion farther from antenna side contains digital/analog circuit blocks.

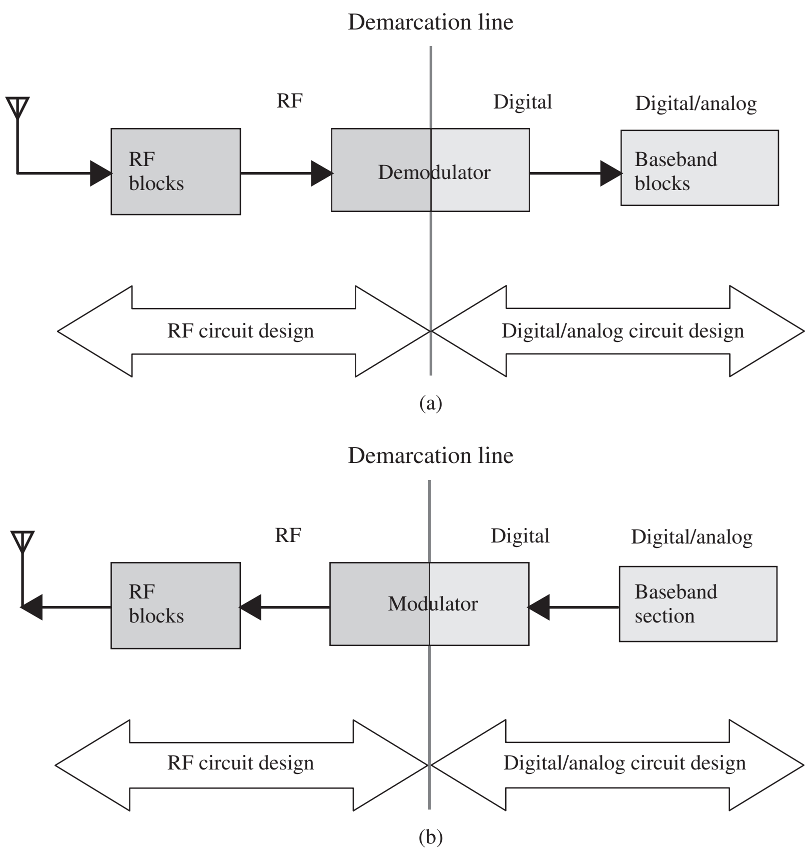

Figure 1.1. Demarcation line in a communication system. (a) Receiver. (b) Transmitter.

In the receiver, the received modulated carrier is usually very weak. After it is power-magnified by the LNA and its frequency mixed down by the mixer, the modulated carrier can be demodulated only if its power is strong enough to suppress the noise power at the input of the demodulator. Typically, the ratio of RF signal power to the noise power at the input of the demodulator is required to be more than 10 dB. It is therefore required that the RF signal be power-transported or power-operated before demodulation. After the demodulator, the digital-type message is demodulated from the RF to the base band. The digital signal is not required to be "power-transported" but is only "status-maintained" or voltage-transported between local blocks for digital signal processing. The voltage represents the status of the signal. For the sake of power saving, the power of the signal is reduced as much as possible. This answers the question why voltage transportation or manipulation or the "status" transportation or manipulation is a logical task in the digital circuit design.

Similarly, in the transmitter, the digital signal is only required to reach the "modulation-effective status level" before the modulator. This implies that the power or voltage of the input digital signal to the modulator could be as low as possible as long as the input voltage or power reaches a level by which the carrier can be effectively modulated. In this case, the digital signal is transported or manipulated between the local circuit blocks and is not required to be power-transported but only voltage-transported. However, the modulated carrier after the modulator must be power-magnified and delivered to the antenna so that the modulated carrier is powerful enough to propagate to a receiver located a long distance from the transmitter.

1.3 CONCLUSIONS

From the discussion in Section 1.2.3, it can be concluded that the power transportation or manipulation, but not voltage transportation or manipulation, is required in the RF blocks before the demodulator in a receiver and after the modulator in the transmitter. The voltage transportation or manipulation, but not power transportation or manipulation, is required in the digital blocks after the demodulator in a receiver or before the modulator in a transmitter.

This is the answer to the question in Sections 1.2.2 and 1.2.3: why is RF circuitry focused on the power while the digital circuitry is concerned about voltage?

It can be seen that the controversy between digital and RF designers is not necessary. The difference in circuit design methodology arises from the different circuit design tasks. The digital circuit is designed for voltage transportation or manipulation, while the RF circuit is designed for power transportation or manipulation.

1.4 NOTES FOR HIGH-SPEED DIGITAL CIRCUIT DESIGN

In digital communication, the synonym of "high speed" is high data rate.

In the case of high digital data rates, the tasks of both types of circuits are unchanged: the RF circuit still works for the power while digital circuit still works for the *status* transportation or operation. However, the design methodology in high data rate digital circuit designs is close to that of the RF circuit design methodology, because of the following reasons:

1. The remarkable variation of a digital circuit design from low speed to high speed is the change of the input and output impedance of a digital block. In the digital circuit design for low speeds, high input and output impedance of a digital block can be obtained from high input and output impedance of a transistor. The input and output capacitance of a transistor can impact on the input or output impedance so that they impact on the rising or dropping time. In the digital circuit design for high speeds, the input and output impedance of a transistor is reduced. The low input and output impedance leads to the necessity of impedance matching in the digital circuit design. Impedance matching is beneficial not only to power transportation but also to voltage transportation. Without impedance matching, the reflected voltage will appear and interfere with the incident voltage. This brings about additional attenuation, additional jitter, an additional cross talk, and eventually an additional bit error to the digital signal.
2. The traditional layout scheme is no longer reliable in the case of digital circuits with high data rates. For example, in the traditional layout for digital circuits with low data rates, the runners are always lined up in parallel so that the entire layout looks nice and neat. However, in the layout for digital circuits with high data rates, the runners lined up in parallel could cause appreciable coplanar capacitance and are coupled with each other, and, consequently, it may cause interference or cross talk. The layout for high-speed digital circuitry must be taken as seriously as for the RF circuitry.
3. The traditional AC grounding scheme for a digital circuit with low data rate is no longer reliable in the case of a digital circuit with high data rate. For high-speed digital circuitry, the AC grounding must be taken as seriously as for an RF circuitry.
4. In a digital circuitry with high data rate, isolation may become a serious problem. Usually, a digital signal is a rectangular pulse while an RF signal is sinusoidal. The former contains a wide-band spectrum while the latter contains a narrow-band spectrum. This implies that a digital circuit with a high data rate is easier to be interfaced with inside or outside interference sources because its frequency spectrum is much wider than that of a digital circuit with low data rate. Isolation between blocks becomes important and should be taken as seriously as for an RF circuitry.

FURTHER READING

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EXERCISES

1. Specify the main difference in task between RF and digital circuit designs.
2. Compare and comment on the task between RF and digital circuit designs when the digital data rate is much less than the RF carrier frequency.
3. What is the difference in digital circuit design between low and high data rate cases?
4. High impedance is beneficial to voltage transportation or manipulation while low impedance is beneficial to power transportation or manipulation. Why?
5. Why is impedance the main parameter in RF circuit design?
6. Why is the normalized impedance regulated as 50 Ω?
7. Assuming that the input capacitance of a MOSFET (metal–oxide–semiconductor field-effect transistor) is $0.15915 \text{ pF} = 1/(2\pi) \text{ pF}$, what is the input impedance for an RF signal if its operating frequency is 10, 100, 1000, and 10,000 MHz, respectively? Also, what is the input impedance for a digital signal to be considered if its digital data rate is 10, 100, 1000, 10,000 Mb/s, respectively, and if its second and third harmonics are as important as the main frequency corresponding to the digital data rate?
8. Why is power the transportation type of an RF signal while status (voltage or current) is the transportation type for a digital signal?
9. Why is impedance matching important in RF but not in digital circuit design when $R \ll f_{RF}$?
10. Why is impedance matching important not only in RF but also in digital circuit design when $R \approx f_{RF}$?

ANSWERS

1. The main difference of task between RF and digital circuit design can be tabulated as follows:

Item	RF Circuit Design	Digital Circuit Design
Transportation type	Power	Status (voltage or current)

2. When the data rate is low, the difference between RF and digital circuit can be tabulated as follows:

Item	RF Module/RFIC	Digital Circuit (Low Data Rate)
Impedance	Low (50 Ω typically)	High (infinity ideally)
Current	High (mA)	Low (μA)
Location in a Communication System		
• *Rx*	Front end (before demodulation)	Back end (after demodulation)
• *Tx*	Back end (after modulation)	Front end (before modulation)
Transportation type	Power (W)	Status (voltage or current)
Impedance matching	Important	Unimportant (usually)

3. In the low digital data rate case, the input or output impedance in the digital circuit is usually high. However, in the high data rate case, the input or output impedance

in the digital circuit is not high because of the existence of the input or output capacitance of the device. Impedance matching becomes effective in the voltage transportation. The voltage will be pumped up when the load resistance is greater than the source resistance, that is, $R_L > R_S$.

4. Low impedance is beneficial to power transportation or manipulation because,

$$P = vi = \frac{v^2}{Z}$$

for a definite voltage, the power becomes high if the impedance is low (say, 50 Ω). On the contrary, high impedance is beneficial to status transportation because

$$v = iZ$$

for a definite current, and the voltage swing becomes large if the impedance is high.

5. The main task of the RF circuit is to transport or to manipulate the power of signal. This is the main reason that the impedance becomes the main parameter to be taken care of in an RF circuit design. The performance of power transportation or manipulation is mainly determined by the status of impedance matching.
6. For a coaxial cable with an air dielectric, in order to maximize the power-handling capability, one could increase the diameter of the inner wire. However, there are two competing effects: the breakdown voltage is increased but the characteristic impedance Z_o would be incresed also, which would tend to reduce the power deliverable to a load. The maximum of the power-handling capability can be reached if the diameters of the inner wire and the outer conductor are well-selected so that a Z_o of 30 Ω is approached. On the other hand, in order to minimize the attenuation of a coaxial cable, there are also two competing effects due to the increase of the inner wire diameter: both of resistance per unit length and the characteristic impedance Z_o would be reduced at the same time, which would tend to an uncertainity of the attenuation. The minimum of the attenuation can be reached if the diameters of the inner wire and the outer conductor are well-selected so that a Z_o of 77 Ω is approached...″ Since 77 Ω gives us minimum loss and 30 Ω gives us maximum power-handling capability, a reasonable compromise is a round average value, Z_o of 50 Ω.
7. The input impedance for an RF signal is 100 kΩ, 10 kΩ, 1000 Ω, and 100 Ω, respectively.
   The input impedance for a digital signal is 33.3 kΩ, 3.3 kΩ, 333.3 Ω, and 33.3 Ω, respectively, if its second and third harmonics are as important as the main frequency corresponding to the digital data rate.
8. In the receiver, RF and digital circuits are located before and behind the demodulator, respectively. The performance of RF circuits must be good in power transportation so that the threshold of the CNR power ratio at the input of demodulator can be reached or exceeded and consequently the demodulation becomes available. On the contrary, the task of the digital circuits after the demodulator is to transport or manipulate the status (voltage or current) of digital signals.
   In the transmitter, digital and RF circuits are located before and behind the modulator, respectively. The task of the digital circuits before the modulator is to transport or manipulate the status (voltage or current) of digital signals. On the contrary, the performance of RF circuits after modulator must be good in power transportation

so that the CNR power ratio at the output of modulator can be radiated to remote places where the receiver antenna is located.

9. When $R \ll f_{RF}$, impedance matching is important in RF but not in digital circuit design because the carrier frequency f_{RF} of RF signal is high, whereas the frequency components of digital signals are low. The input/output impedances in RF circuits are low, while the input/output impedances in digital circuits are high. Impedance matching is important when the input/output impedances of a circuitry are low, but it is not important when the input/output impedances of a circuitry are high.
10. When $R \approx f_{RF}$, impedance matching is not only important in RF but also in digital circuit design because both the carrier frequency f_{RF} of RF signal and the frequency components of digital signals are high. Both of the input/output impedances in RF circuits and the input/output impedances in digital circuits are low. Impedance matching is important when the input/output impedances of a circuitry are low.