Frequency-Tunable Antenna by Input-Impedance-Tunable CMOS RF-Frontend

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***Abstract*—Variable-impedance matching between the antenna and the RF-frontend provides several potential advantages, including changing operational frequency, compensating for unintentional mismatch, improving scanning capability, and reducing noise and interference signal levels. In this article a concept of tuning the operational band of an antenna by variable-impedance matching is presented. In this investigation a 65 nm CMOS RF-frontend capable of changing its input-impedance has been used to tune the operational band of a microstrip antenna. It is shown that by properly selecting the input-impedance of the RF-frontend, the operating frequency of the antenna can be shifted, which increases the total operational bandwidth from 10 MHz to more than 30 MHz.**

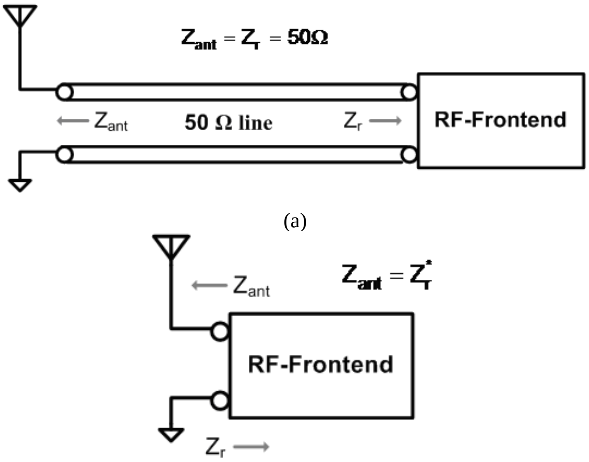
Keywords—variable impedance; frequency tuning; CMOS; RF-frontend, antenna.

I. INTRODUCTION

For many decades, 50 Ω transmission lines and connectors have been extensively used to provide a standard interface between antennas, RF-frontends and measurement equipment. This standardization, however, severely limits the flexibility of RF-frontend and antenna design. The 50 Ω impedance value has several practical advantages, but is neither derived from any physical limit, nor does it assure the best performance for a system. Avoiding or minimizing such 50 Ω impedance transformation in the RF-frontend will significantly reduce design restrictions and enhance total system performance [1-2].

The variable-impedance matching can be achieved by a separate reconfigurable matching network [3-4] or it can be integrated in the RF-frontend chip. The latter can be useful to reduce size and cost while producing a larger variety of resistance and reactance values. In this article we propose the concept of variable-impedance matching of the antenna using an input-impedance-tunable CMOS RF-frontend. The proposed concept has the advantages of frequency reconfiguration, compensating for unintentional mismatch, improvements in scanning capability, and more. The authors believe that this is one of the first published designs where the antenna's operational band has been tuned directly by the RF-frontend.

The paper is organized as follows: the concept of variable-impedance matching is discussed in Section 2. The input-impedance-tunable CMOS RF-frontend is detailed in Section 3. An example of variable-impedance matching for a microstrip antenna is presented in Section 4. Finally the conclusions are drawn in Section 5.



(a)

(b)

Fig. 1. (a) Conventional impedance-matching, (b) Variable-impedance matching

II. THE CONCEPT OF FREQUENCY TUNING BY VARIABLE INPUT-IMPEDANCE OF THE RF-FRONTEND

In Fig. 1 the concept of variable-impedance matching has been illustrated. Unlike conventional fixed-impedance matching (Fig. 1a), here the antenna is directly connected to the RF-frontend (Fig. 1b). Therefore, the input-impedance of both the antenna (Z_{ant}) and the RF-frontend (Z_r) is not obliged to be 50 Ω. From power-wave theory [5] we know that the reflection coefficient (Γ) will be zero when the antenna and the RF-frontend impedances are complex conjugates (maximum power transfer) of each other:

$$\Gamma = \frac{Z_{ant} - Z_r^*}{Z_{ant} + Z_r} \tag{1}$$

It is worth to point out here that when the reference impedance (in this case Z_r) is complex, the power-wave definition of reflection coefficient is more meaningful than the more commonly used travelling-wave definition. Equation (1)

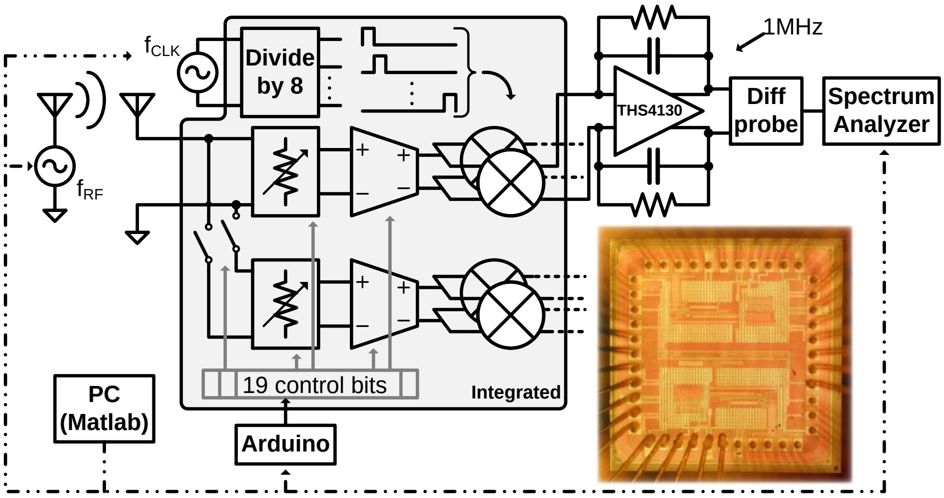


Fig. 2. Block diagram of CMOS RF-frontend implementation and measurement setup

is defined from the propagation of power rather than the physical waves in the transmission lines.

The non-standard impedance matching, depicted in Fig. 1b, provides extra flexibility in antenna and RF-frontend design and the overall optimization process [6]. In addition, a variable-impedance matching network can be established if the input-impedance of the RF-front is tunable.

Many antenna elements show high radiation efficiency outside their instantaneous frequency band. As input-impedances of most antennas are highly frequency dependent, a fixed 50 Ω impedance transformation only allows a good matching within a limited frequency range. For the concept presented in Fig. 1b, the input-impedance of the RF-frontend (Z_r) can be changed to match the antenna input-impedance (Z_{ant}) over a large frequency band. In this way, frequency reconfigurable or tunable antennas can be realized. This approach avoids the use of switches in the radiating antenna element, and therefore reduces complexities and parasitic effects of RF-switches and their control lines.

III. CMOS RF-FRONTEND WITH VARIABLE-INPUT-IMPEDANCE

Fig. 2 shows the implementation of two RF-frontends in a single 65 nm CMOS IC. The receivers can be (dis)connected by on-chip low-ohmic switches, and can change their input impedance to provide 50 Ω input matching in both single-receiver and two-receiver modes. The two-receiver mode is originally designed to perform crosscorrelation spectrum sensing with attenuators in front (explained in detail in [7]). It has a programmable impedance setting to match to 50 Ω, 100 Ω and a range around those values. This chip is exploited here to experimentally validate the concept of frequency tuning with variable impedance settings.

Each receiver consists of a discrete-step attenuator and a low-noise transconductance amplifier (LNTA) for input power to current conversion. At baseband, an external transimpedance amplifier (TIA) with RC-feedback is used to convert the current to a voltage, followed by a differential probe to connect to a spectrum analyzer. The mixer is driven by a master clock at 8 times the mixer frequency, and can operate from roughly 100 MHz to 1GHz. In the measurements, the mixer frequency was chosen to be 1 MHz below the RF- input frequency, such that all measurements are performed at 1 MHz IF.

Each attenuator is separately controlled by 6 control bits, set via a serial interface with an external microcontroller. Five of these bits individually turn on or off one of the 5 attenuator branches (0 dB, 2 dB, 6 dB, 10 dB, and 16 dB attenuation). The sixth control bit determines whether each branch (except for the 0dB setting) should provide 50 Ω or 100 Ω input impedance. This is schematically shown in Fig. 3. In principle, these 6 bits thus provide for 36 different settings, each with different input impedance.

As the attenuator is a resistive PI-type attenuator, its input impedance is partly determined by the load, which in this implementation is the LNTA. The LNTA is shown in Fig. 4. It has a common-gate input stage, designed with two identical transistors, each providing 100 Ω input impedance. Two control bits turn on or off these two common-gate transistors to change the LNTA input impedance to 50 Ω, 100 Ω, or high impedance values (capacitive). The switches connecting the two receivers have 3 control bits, as shown in Fig. 5.

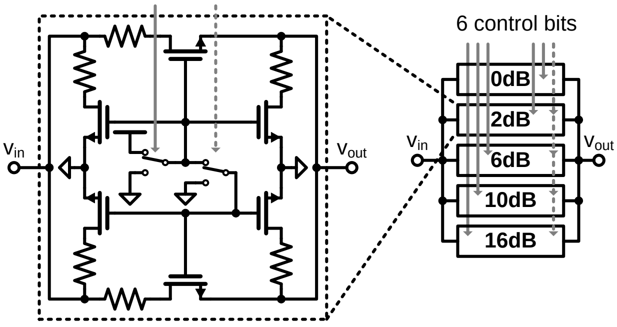


Fig. 3. Attenuator cell

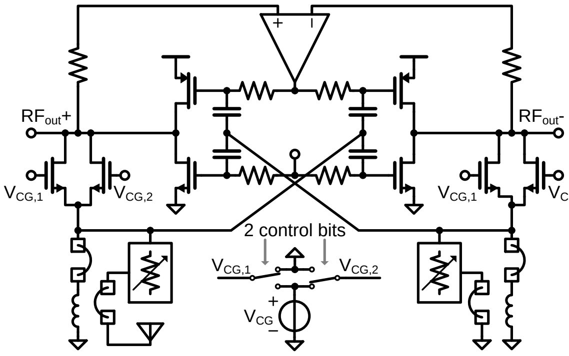


Fig. 4. Implementation of LNTA and input-impedance control

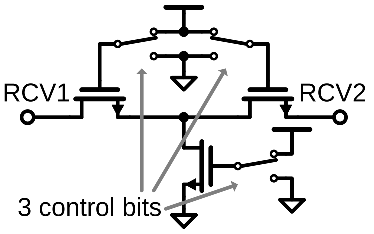


Fig. 5. Connection between the two receivers and control

IV. AN EXAMPLE OF NON-STANDARD IMPEDANCE MATCHING FOR MICROSTRIP ANTENNA

To experimentally verify the concept of variable-impedance matching, a narrowband microstrip antenna has been chosen as the reference antenna (see Fig. 6). The measurement setup is illustrated in Fig. 2. Here the dielectric wedge antenna of [8] has been used as the transmit antenna while the microstrip antenna has been used as the receive antenna followed by the impedance-tunable RF-frontend. The reflection coefficient and the input impedances of this element are presented in Fig. 7 and good agreement has been observed between the numerical and experimental results. The microstrip antenna radiates at 595 MHz with an instantaneous bandwidth of 10 MHz ($|S_{11}| \le -10\,dB$) for 50 Ω reference impedance. However, the antenna shows an almost constant directivity from 550 MHz to 650 MHz which implies that the antenna possesses sufficient radiation efficiency in this band, hence adequate radiated power can be expected within this band when properly matched to the reference impedance (It is worth to point out here that only providing impedance match will not assure that the antenna will radiate efficiently and sufficient antenna gain over the whole tunable-band is needed). By changing the matching impedance, in this case the input impedance of the CMOS RF-frontend, the operational band can be tuned.

From the experimental results of the antenna input impedance (see Fig. 7) we can now determine the required input impedances of the CMOS chip. To tune the operational frequency band, the settings of the receiver module has been altered (as explained in the previous section) to achieve these required values. In Fig. 8 and Fig. 9, the input impedance of the antenna has been compared with the input impedance of the CMOS chip for two different settings as typical examples. For setting 1 and 2 the conjugated impedance matching occurs around 570 MHz and 600 MHz, respectively. In the frequency range between 560 and 580 MHz the antenna is highly inductive (see Fig. 8). Therefore, when the impedance setting of the chip is set to a capacitive value, the received signal strength reaches its highest value in this band as demonstrated in Fig. 10. Similarly, to assure good matching around 600 MHz an almost purely resistive 30 Ω (see Fig. 9) input impedance has been selected which in turn shifted the peak of the received signal to 600 MHz and therefore, the total operational bandwidth of the antenna increases from 10 MHz to more than 30 MHz.

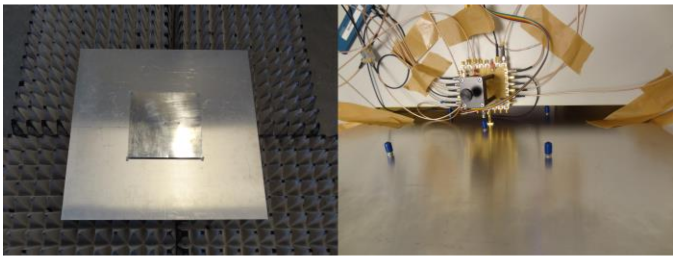


Fig. 6. Antenna prototype (left) and CMOS chip attached at the back of the antenna (right)

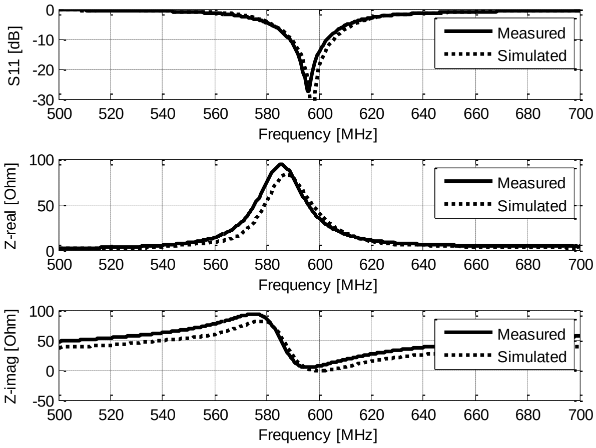


Fig. 7. Numerical and measurement results of reflection coefficient (for 50 Ω reference impedance) and input impedances of the microstrip antenna

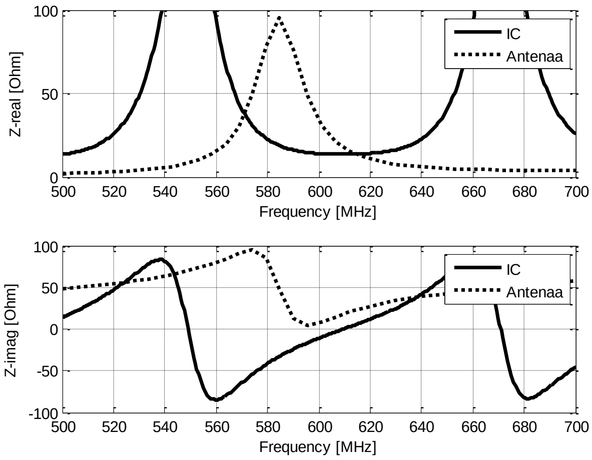


Fig. 8. Impedance comparison of the antenna and the IC for setting 1

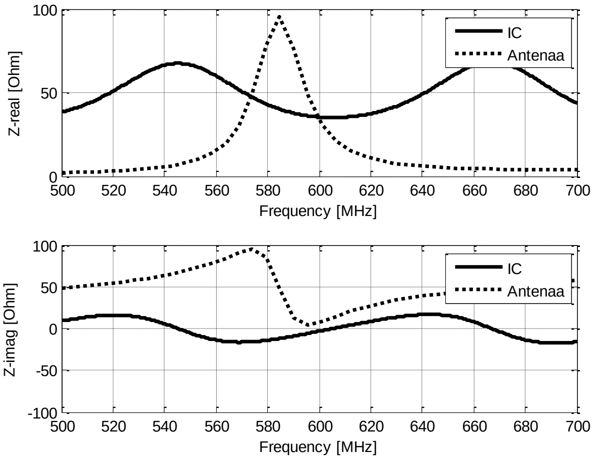


Fig. 9. Impedance comparison of the antenna and the IC for setting 2

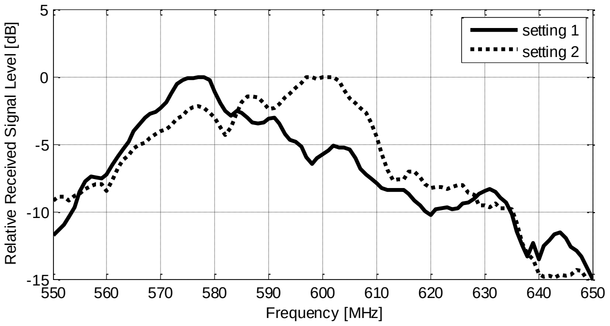


Fig. 10. Received signal level for variable impedances

V. CONCLUSION

In this paper a concept of an antenna and RF-frontend co-design with variable-impedance matching is investigated. A CMOS chip has been used as a receiver with variable input-impedance. An analysis of tuning the operational band of the antenna by varying the input impedance of the RF-frontend has been conducted. To tune the operational frequency band, the impedance settings of the RF-frontend have been altered. Accordingly the operational band shifted and we observed extension of the antenna overall operational bandwidth. While for conventional 50 Ω loading the instantaneous bandwidth equals 10 MHz, a non-standard impedance matching increases the total bandwidth by a factor of three at least. The frequency range can be further enhanced by realizing a closer integration of the antenna with the RF-frontend.

DISCUSSION AND OUTLOOK

This concept of variable-impedance matching has significant fundamental advantages. Some of them are listed below.

1. For a narrowband antenna, the total operational bandwidth can be improved by tuning the instantaneous band.

2. For dual- or multi-band antennas, an operational band can be selected by matching the frontend to the corresponding impedances of the specific band while suppressing the signals from other bands by intentional mismatch.

3. Selection of sub-bands for wideband antenna systems. This will provide band selectivity, reduce the noise bandwidth and relax the requirements for the frontend filters.

4. Compensate for temporal antenna mismatch due to detrimental effect of objects in the close vicinity of the antenna (particularly important for hand-held cellular devices).

5. Compensate for mismatch caused by manufacturing process.

6. For phased-array antennas, maintain good matching for large scan angles and thereby increase scan volume.

7. Reveals opportunity to use antenna structures for which the inherent input impedance is not 50 Ω.

8. Useful to reduce noise factor of the RF-frontend [6].

Owing to these benefits there is a strong possibility that variable-impedance matching will be extensively used for many applications, such as communication, cognitive radio and radar.

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