Chapter 5

RF/Baseband Co-verification Methodology

The chapter presents the proposed RF/Baseband co-verification methodology for wireless transceiver designs. The necessity of RF/Baseband co-verification is addressed in Section 5.1. The co-verification methodology is described in Section 5.2.

5.1 Necessity of RF/Baseband Co-verification

The urgent demands on low-cost wireless multimedia applications have drastically driven the integration of both analog/RF and digital/baseband building blocks into a wireless transceiver system on a chip (wirless SOC). The design complexity becomes extremely high not only in the technology involved but also the design methodology. Figure 5.1 illustrates a typical wireless LAN transceiver system consisting analog/RF and digital/baseband as PHY layer, MAC layer, memory systems as well as the system interface. The wireless connetivity is established by well cooperations in each layer. That is, from the bit/frame/packet error rate to the sensitivity of WLAN specification, the performance of communication must be assured at the very beginning of the design phase and at every part of the system in order to

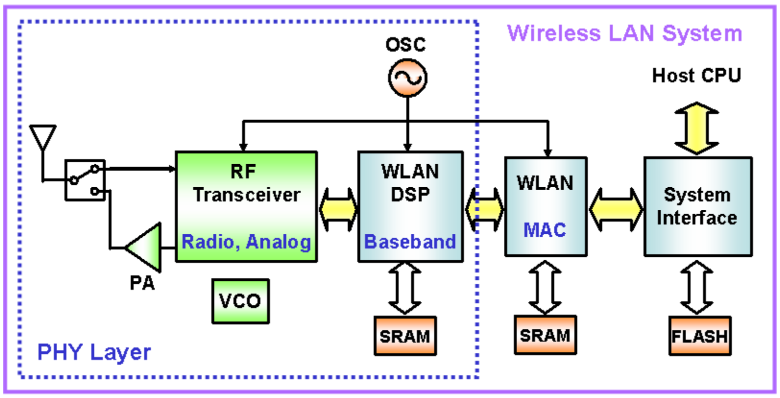

Figure 5.1: Wireless LAN transceiver system.

ensure robust wireless connectivities.

Figure 5.2 shows the top-down design flow of a wireless transceiver system. The design flow starts from system partition, module design, integration, verification and finally fabrication. The system consists of so many parts that divide and conquer is the conventional approach to tackle the design complexity: By separating the design of analog/RF part and digital/baseband part, it is easy to simplify the complexity and save the design cycle. The only language used without translation for both transceiver parts is signal to noise ratio (SNR). RF designers struggle for low noise figure to assure the required SNR while baseband designers endeavor to minimize implementation loss of demodulation algorithms from AWGN basis. The seperation avoids midterm verfication of the whole system performance, since the only thing to be ensured is the required SNR at both parts.

The scenario works very well for systems of single-carrier modulations, since the modulated carrier can be represented in complex format (I/Q) and the error vector magnitude measured by RF and baseband parts are target on the same single carrier. Assume the information to modulate a single carrier is $g(t) = I(t) + jQ(t)$,

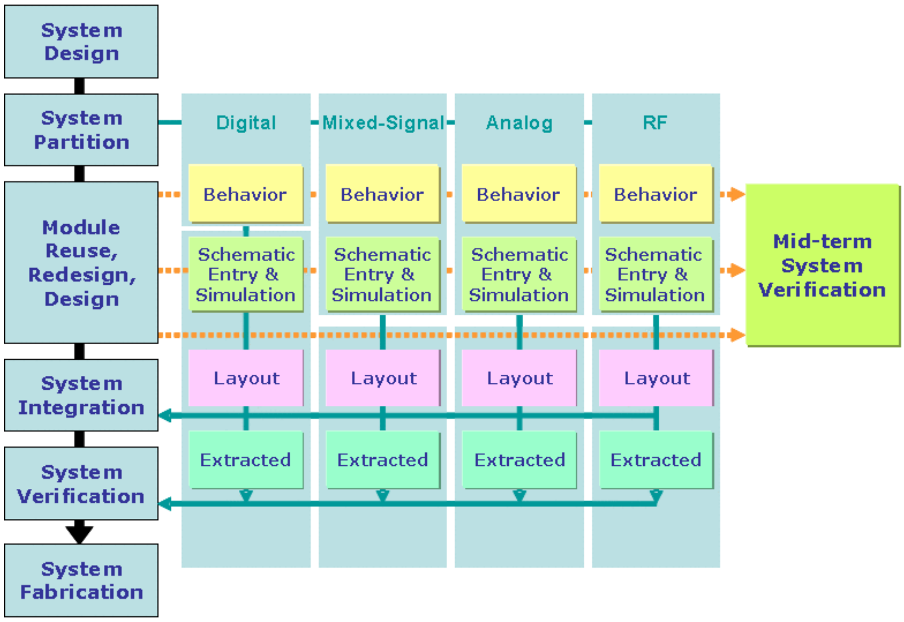

Figure 5.2: Wireless SOC top-down design flow.

the modulated RF carrier can be expressed as

$$
\begin{aligned}
s(t) &= \Re e\{g(t)e^{j\omega_c t}\} \\
&= I(t)\cos\omega_c t - Q(t)\sin\omega_c t
\end{aligned}
\tag{5.1}
$$

The down-converted I/Q mismatched baseband I/Q signals at the analog/RF transceiver part are

$$
\begin{aligned}
x_{BB,I}(t) &= I(t) \\
x_{BB,Q}(t) &= (1+\epsilon)\left(I(t)\sin\theta - Q(t)\cos\theta\right)
\end{aligned}
\tag{5.2}
$$

which is exactly the same as that measured by the digital/baseband transceiver.

However, the demand of higher data rate and lower cost have made multi-carrier modulation more attractive. Orthogonal frequency division multiplexing (OFDM) is one of the multi-carrier modulation schemes and has been adopted in many wireless standards such as IEEE 802.11a/g, 802.16 and etc. [2]-[10]. The multi-carrier OFDM symbol can be expressed as

$$g(t) = \sum_{k=1}^{k=N} (I_k + jQ_k) e^{j\frac{2\pi k}{T_s}t} \tag{5.3}$$

where $I_k + jQ_k$ is the complex baseband information for each subcarrier $e^{j\frac{2\pi k}{T_s}t}$. The modulated RF carrier can be expressed as

$$\begin{aligned} s(t) &= \Re e\{\sum_{k=1}^{k=N} (I_k + jQ_k) e^{j\frac{2\pi k}{T_s}t} e^{j\omega_c t}\} \\ &= \sum (I_k \cos k\omega_s t - Q_k \sin k\omega_s t) \cos \omega_c t \\ &\quad - \sum (Q_k \cos k\omega_s t + I_k \sin k\omega_s t) \sin \omega_c t \\ &= I_{mc}(t) \cos \omega_c t - Q_{mc}(t) \sin \omega_c t \end{aligned} \tag{5.4}$$

The I/Q signals measured by RF parts is $\langle I_{mc}(t), Q_{mc}(t)\rangle$ and is no longer that measured by baseband parts $\langle I_k, Q_k\rangle$. In addition, the error vector magnitude measured at the analog baseband of a direct conversion receiver is

$$\begin{aligned} |\mathbf{e}| &= (1+\epsilon)\left(I_{mc}(t)\sin\theta - Q_{mc}(t)\cos\theta\right) + Q_{mc}(t) \\ &\neq \sum \left[(1+\epsilon)\left(I_k \sin\theta - Q_k\cos\theta\right) + Q_k\right] \end{aligned} \tag{5.5}$$

and can not be evenly distributed to each subcarrier at digital baseband. Moreover, the error vector may be caused by the noise figure of the receiver, intermodulation distortion, phase noise of LO signals, dc offset and so on. Therefore the overall error vector can be expressed as

$$\mathbf{e}_{tot} = \mathbf{e}_{NF} + \mathbf{e}_{IM} + \mathbf{e}_{PN} + \mathbf{e}_{IQ} + \mathbf{e}_{OS} + \cdots \tag{5.6}$$

$$\begin{aligned} |\mathbf{e}_{tot}| &= |\mathbf{e}_{NF} + \mathbf{e}_{IM} + \mathbf{e}_{PN} + \mathbf{e}_{IQ} + \mathbf{e}_{OS} + \cdots| \\ &\neq |\mathbf{e}_{NF}| + |\mathbf{e}_{IM}| + |\mathbf{e}_{PN}| + |\mathbf{e}_{IQ}| + |\mathbf{e}_{OS}| + \cdots \end{aligned} \tag{5.7}$$

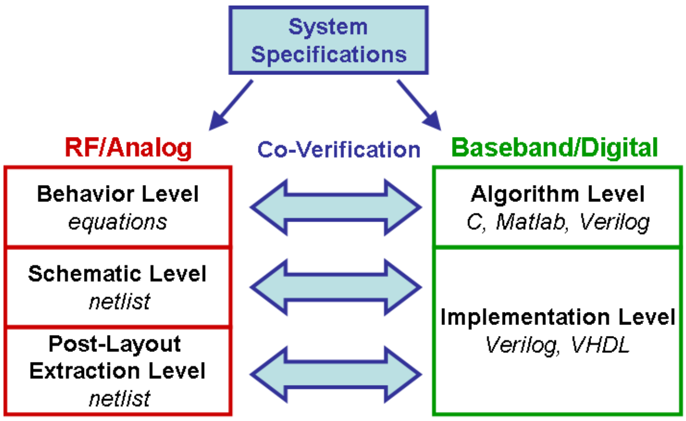

Figure 5.3: RF/Baseband co-verification platform.

Unfortunately, these impairments are not independent and can not be separated in multi-carrier modulation systems. In other words, any impairment of RF transceiver causes a lump effect on the desired signal and cannot be distinguished independently for each subcarrier. Therefore, co-verification of RF and baseband becomes more and more critical for robust design of wireless SOC.

5.2 RF/Baseband Co-verification Methodology

5.2.1 Co-verification Platform

Since RF/analog and baseband/digital transceivers deal with different styles of signals, direct simulation of both parts is not possible to co-verify both parts unless some sorts of abstraction for both parts are concurrently applied. C-language-based behavior models are usually used as co-verification of RF and baseband parts at system partition stage, however it lacks of accurate prediction capability or requires sophisticated crafts to build precise models. The transceiver designs are divided and conquered independently without any co-verification during the design process.

Nowadays EDA tools have more powerful features that allow the co-simulation of different abstraction levels of electronic systems, such as co-simulation between transistor level with verilog, or transistor level with C-language level. The ability of co-simulation of various abstraction levels is crucial for the development of system on a chip. Figure 5.3 shows conceptual co-verification platform. RF transceiver design follows top-down design flow: behavior, schematic to layout levels; baseband transceiver design starts from algorithm to implementation levels. The co-verification should be performed by the co-simulation of both parts at the behavior level, schematic level and post-layout level to ensure the system performance during the design process. The simulation computing time for co-verification depends on the abstraction level and the complexity of the design. The abstractions for baseband are based on verilog, Matlab or C-language, which is for high-level design. For RF/analog, the abstraction usually used is transistor SPICE model, which is accurate but complicated.

5.2.2 Performance Measure for Co-verification

The choice of the performance measure is critical for RF and baseband co-verification, since the main idea for co-verification is not only to verify performance but to feedback information for RF and baseband parts to improve the whole transceiver design. Ultimately, the best way to measure the performance of wireless transceivers is to directly measure the bit error rate (BER). This can be done by simulate BER in the co-verification platform. However, it takes too much simulation time and BER is not really relevant to any information to improve RF design.

The SNR parameter relates RF and baseband transceiver performance and should be able to provide information to enhance RF design. However, unlike noise figure, it is not easy to direct measure the SNR of RF/analog transceiver part. Instead of direct simulation of SNR, error vector magnitude (EVM) is adopted as the performance co-verification measure for RF and baseband transceivers. Since EVM can be regarded as the inverse of SNR (see Appendix A), the relation of

BER to SNR is easily obtained without the necessity of direct BER simulation. In addition, after EVM simulation, we can obtain any system-level impairments of direct conversion receivers such as I/Q mismatch and DC offset and feedback to RF circuit design improvements.