# A Mixed-Domain Modeling Method for RF Systems

Zhimiao Chen, Zhixing Liu, Lei Liao, Ralf Wunderlich, Stefan Heinen
Chair of Integrated Analog Circuits and RF Systems,
RWTH Aachen, 52074, Aachen, Germany, ias@rwth-aachen.de

***Abstract*—This paper introduces a mixed domain event-driven modeling method for RF systems. The circuit behaviors are modeled in time/frequency domain adaptively combining with the equivalent baseband representation of each spectral component. Comparing to traditional baseband modeling methods or harmonic balance simulation techniques, this mixed domain method loose the requirements of relations among carrier frequencies of spectral components, and therefore can be widely used in mixed-signal circuit modeling. Furthermore, this method brings in a great simulation speed up over the simulation in passband signal abstraction, while the modeling accuracy can be guaranteed to meet the requirements of functional verifications.**

## I. Introduction

The verification of RF systems integrated in wireless SoC devices is attracting more and more attentions when the complexity of the mixed-signal circuits is growing. The performance simulations of mixed-signal circuits are mainly addressed by SPICE based analog simulators. It is still a big challenge for the pre-tapeout verification, due to the low simulation efficiency when the matrix size of ODEs (Ordinary Differential Equations) is huge. Some other solutions have to be proposed to solve the simulation efficiency problem.

Fast SPICE simulation technique has been maturely applied in many EDA softwares. It optimizes the calculation process of analog simulators by applying matrix simplification methods [1]. However, there is still a big gap between the simulation speed it can achieve and the simulation speed the state-of-the-art mixed-signal circuits requires. PSS [2] or harmonic balance simulation methods [3] are used to solve the RF circuits with high simulation performance. PSS analyzes the periodic properties of circuits in time domain, while the harmonic balance method carries the numerical calculations at harmonics of root frequencies. The prerequisite of the two methods is the periodic or quasi-periodic property of the circuits. They are not widely feasible in the entire wireless SoC, which contains both periodic RF front-end and non-periodic digital circuitry.

Building HDL behavioral models for analog circuit is another idea [4]. The behavioral models of analog part, combing with the TLM digital models, can enable the functional verification of entire SoC using much faster digital simulators, when the analog behavior can be described using true event-driven methods [5]. However, the entire simulation speed will be pulled down by solving high frequent RF front-end. The simulator must assign a very small time step to sample the high frequent RF signals without distortions.

The RF signals are represented using their baseband equivalence [6] to speed up the simulations. Unfortunately, this traditional baseband modeling methods cannot process the distortions of carriers. Too much sacrifice of simulation efficiency is paid to trade for the increase of simulation speed. This work aims to propose a better solution compromising the various requirements of mixed-signal circuits with great simulation speed increase.

## II. Mixed-domain modeling method

The idea of mixed-domain modeling method is originated from the traditional baseband modeling method. In the baseband modeling method, the time step of simulator can be much bigger than sample RF signals, while they are converted to their baseband equivalence.

Through some conversions (baseband equivalent), the circuit behaviors with different properties (signals working in baseband or RF band) can be simulated without compromising the worst case (small time step of the simulator to cater RF signals). The conversions should be able to trade the simulation accuracy for simulation efficiency, modeling complexity, or other figures of merit. The loss of simulation accuracy brought in by the conversions should be reduced as small as possible to make the simulation results still reliable. Hence, it is critical to deliberately give the proper conversion methods.

Unfortunately, the traditional baseband equivalent method has lost too much accuracy as the carrier distortions are ignored, which strongly affect the performance of a RF receiver front-end. Harmonic balance method is proposed allowing the verification engineers to observe what happens not only at root frequency but also at its harmonics. In RF bands, things are complicated. The signals from adjacent channels or blockers may appear in any frequency band to degrade the performance of RF front-end. A universal representation of signals appearing in RF systems is used here:

$$\begin{aligned} S_{RF}(t) &= \sum_n \{I_n(t)\cdot cos(2\pi f_n t) - Q_n(t)\cdot sin(2\pi f_n t)\} \\ &= \sum_n \{I_n(t) + jQ_n(t)\}\cdot e^{j2\pi f_n t} \end{aligned} \tag{1}$$

Using this representation, firstly, all signals in RF systems can be covered without concerning whether the circuit behaviors are periodic or quasi-periodic. Secondly, the signals working in baseband can also be represented when $n = 1$, and $f_n = 0$. The processing of the entire system can be unified. Furthermore, the interactions among signals and interferers may generate new spectral components at any possible frequencies. These new components will not be ignored using this representation. Another important concern is the simulation speed. In general, the simulation speed is directly related to the bandwidth or maximum frequency of sub signals. This representation can separate a spectral component with wide bandwidth into some neighboring signals with much narrower bandwidth, and can be sampled with much larger time step by the simulator.

The signals in RF systems are now described as a set of spectral components:

$$\mathbf{S}(t): \quad \{f_n, I_n(t), Q_n(t), n \in \mathbb{N}\} \tag{2}$$

The frequency modulation information can be equivalent to the time varied phase modulation information. Therefore, the carrier frequency component $f_n$ can be regarded as constant during the simulation. The processing of high frequent signal $S_{RF}(t)$ is now degraded to the processing of much lower frequent in-/quadrature phase components $I_n(t)$, $Q_n(t)$.

The equivalence mentioned above converts the signals from RF band to baseband. Further conversions are required. For example, in mixed-signal system, the circuit behaviors are viewed in both time domain and frequency domain. But the modeling and simulation of circuit behaviors have to be universalized in time domain. In some cases, it makes the models complex, and damages the simulation accuracy. Some times, it even causes the entire simulation unstable.

For example, for a PPF (Poly-Phase Filter), which is used in RF front-end for the purpose of image rejection, the behavior is given as:

$$\begin{aligned} &Y_I(j\omega) + jY_Q(j\omega) = \\ &\{X_I(j\omega) + jX_Q(j\omega)\} \cdot \{H_I(j\omega) + jH_Q(j\omega)\} \end{aligned} \tag{3}$$

If it is described in time domain, there is,

$$\begin{aligned} y_I(t) + jy_Q(t) &= \{x_I(t) + jx_Q(t)\} * \{h_I(t) + jh_Q(t)\} \\ y_I(t) &= x_I(t) * h_I(t) - x_Q(t) * h_Q(t) \\ y_Q(t) &= x_Q(t) * h_I(t) + x_I(t) * h_Q(t) \end{aligned} \tag{4}$$

In the model of PPF, the transfer functions of $h_I(t)$ and $h_Q(t)$ are given according to their Laplace transfer function in frequency domain. The continuous behavior has to be discretized in simulations. This process will bring in the loss of accuracy. For PPF, the conversion from prototype low pass filter to its complex bandpass counterpart will double the order of transfer function. The mismatch between original continuous behavior and the discrete equivalence may finally result in the failure to calculate the convergent simulation results. Out of the consideration of modeling effort and the simulation accuracy, it is better to describe the behaviors directly in different domains respectively. The signals should be converted to connect the processing in different domains based on FFT (Fast Fourier Transform) and IFFT (Inverse FFT) as shown in Fig. 1.

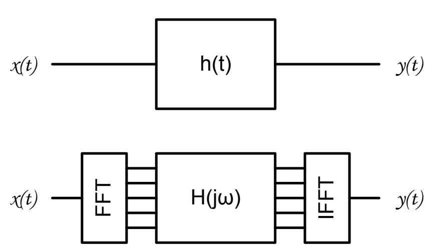


Fig. 1. Process circuit behavior in frequency domain

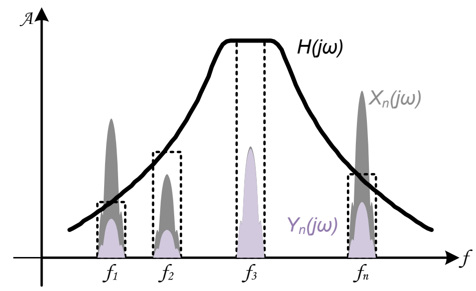


Fig. 2. Set of sub signals passing through filter

Combing with the baseband conversion mentioned above, a set of spectral components passing through a filter will be processed as shown in Fig. 2.

$$\begin{aligned} Y(j\omega) &= X(j\omega) \cdot H(j\omega) \\ \sum_n Y_n(j\omega) * e^{j2\pi f_n} &= \sum_n X_n(j\omega) * e^{j2\pi f_n} \cdot H(j\omega) \\ \sum_n Y_n(j\omega) &= \sum_n X_n(j\omega) \cdot H(j(\omega + 2\pi f_n)) \end{aligned} \tag{5}$$

When the bandwidth of spectral component is small enough, $H(j(\omega + 2\pi f_n))$ can be approximated as $H(j2\pi f_n)$ with constant amplitude and phase transfer. This approximation reduces a lot of signal processing effort in the filter. When the spectral component has relatively wide bandwidth, the variance of filter amplitude and phase transfer cannot be ignored then.

From the experience from PPF modeling, it is better to avoid building $H(j(\omega + 2\pi f_n))$ by generating complex bandpass counterpart from its prototype low pass filter. Instead, we use $sinc$ function as the base function to build up the transfer curve of $H(j(\omega + 2\pi f_n))$ as shown in Fig. 3. There is:

$$\begin{aligned} H(j\omega) &= \sum_{m=-M}^{M} A_m H_0(j\omega) \\ &= \sum_{m=-M}^{M} A_m sinc\{\frac{\frac{M}{F_s}(\omega - m\frac{\pi F_s}{M})}{2}\} \end{aligned} \tag{6}$$

where, $Fs$ is the bandwidth of the spectral component, $2M+1$

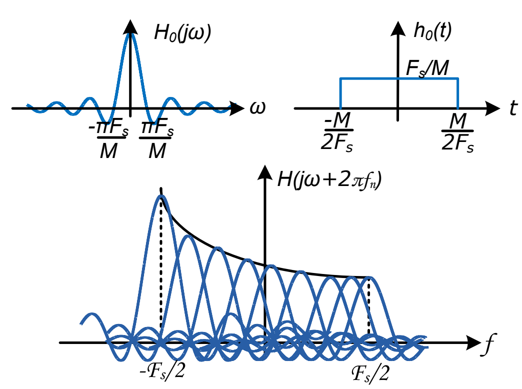


Fig. 3. Modeling filter for sub signals using sinc base function

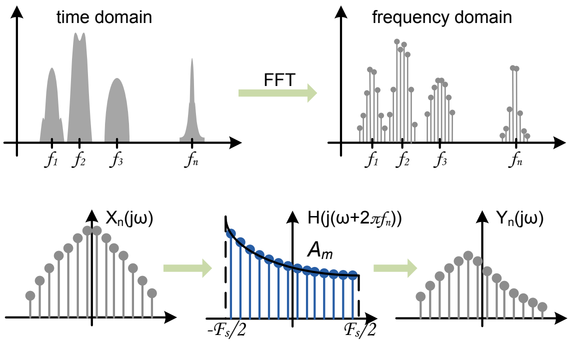

Fig. 4. Modeling filter for sub signals in frequency domain

is the total number of the base functions to build up the transfer curve, and $A_m$ is the complex amplitude of the transfer curve at the certain frequency position.

For the time domain, there is:

$$
\begin{aligned}
h(t) &= \sum_{m=-M}^{m=M} A_m h_0(t) e^{j\frac{m\pi}{M}F_s t} \\
y(t) &= h(t) * x(t) \\
&= \sum_{m=-M}^{m=M} A_m \frac{F_s}{M} e^{j\frac{m\pi}{M}F_s t} \int_{t-M/2F_s}^{t+M/2F_s} e^{-j\frac{m\pi}{M}F_s \tau} x(\tau)\mathrm{d}\tau
\end{aligned}
\tag{7}
$$

In the discrete view, there will be:

$$
y[k] = \sum_{m=-M}^{M} \frac{A_m}{M} e^{-j\frac{m\pi}{2M}} \frac{sin(\frac{m\pi}{2M})}{\frac{m\pi}{2M}} \sum_{l=k-M/2}^{k+M/2-1} x[l] e^{j\frac{m\pi}{M}(k-l)}
\tag{8}
$$

Now go back to Fig. 1, when the signals are converted to frequency domain, the processing will become simpler as shown in Fig. 4. The transfer curve of shifted filter is sampled in frequency domain. The samples are used to multiply with the FFT coefficients of the input spectral component to generate the FFT coefficients of the output spectral component. After IFFT conversion, the corresponding time domain signals can be calculated.

In general, the mixed-domain modeling method first reconstructs the signal as the vector of spectral components with different carrier frequencies. The processing of signals at RF domain is converted to the processing of these components at equivalent baseband domain. Meanwhile, the mixed-signal circuits modeling is separated according to the behavior descriptions in time domain or frequency domain. It bridges the processing in time/frequency domain through FFT/ IFFT.

## III. Implementation for RF Systems

This mixed-domain modeling method is implemented for RF systems using SystemC. In SystemC, a user defined data type is introduced to cover the new signal structure. The data type **bb_sig_vector** and **spectral_sig_vector** stores the vector of spectral components described in time domain and its Fourier coefficients. The data type **TS_sig** as shown in Fig. 5 contains the time domain and frequency domain vectors. FFT/IFFT is called to convert signals from one domain to the other when checking the flags of **time/frequency_domain_valid**.

Operators overloading is also important to reduce the complexity of this mixed-domain modeling method. In general, the mixed-signal behaviors can be described as the combination of basic arithmetic and logic operators. The overloading of these operators and some related basic functions can keep the behavior description unchanged. It also enables automatic switch between different signal abstractions for the behavioral models. For the data type defined above, the overloading of operator *multiply* in time domain is given as an example:

$$
\begin{aligned}
y = x_1 \times x_2, \quad & y = \{< f_n, I_n, Q_n >, n \in [1, N]\} \\
& x_1 = \{< f_k, I_k, Q_k >, k \in [1, K]\} \\
& x_2 = \{< f_l, I_l, Q_l >, l \in [1, L]\} \\
& f_n \in \{f_k + f_l\} \cup \{f_k - f_l\}
\end{aligned}
\tag{9}
$$

for each $f_n$, the corresponding $I_n$, $Q_n$ are:

$$
\begin{aligned}
I_n &= \frac{1}{2}(I_k \cdot I_l \mp Q_k \cdot Q_l) \\
Q_n &= \mp\frac{1}{2}(Q_k \cdot I_l \pm I_l \cdot Q_l)
\end{aligned}
\tag{10}
$$

The convolution function in time domain can be realized by multiplying in frequency domain as below:

```
TS_sig out = conv(TS_sig in1, TS_sig in2)
{
  if(!in1.freq_domain_valid) in1.fft();
  if(!in2.freq_domain_valid) in2.fft();
  TS_sig out;
  spectral_sig temp;
  for(int i=0; i<in1.freq_vector.size(); i++){
    for(int j=0; j<in2.freq_vector.size(); j++){
      temp = in1.freq_vector.at(i)*in2.freq_vector.at(j);
      out.freq_vector.push_back(temp);
    }
  }
  //combine items of out.freq_vector with the same fc
  //sort out.freq_vector with ascending fc
  out.freq_domain_valid = true;
  return out;
}
```

In a RF front-end as shown in Fig 6, the circuit behaviors are separated in different domain for modeling purpose. The noise behavior and weakly nonlinear behavior of LNA (Low Noise Amplifier) are modeled in RF time domain, while the bandpass characteristic is modeled in frequency domain. Similar arrangement is given for other functional blocks like mixer, PPF in the front-end and CP(Charge Pump), loop filter, or VCO(Voltage Control Oscillator) in PLL (Phase Locked Loop). The digital cells still remain in original time domain so that the TLM models can be directly used.

## IV. Simulation Results

The proposed method is applied to the RF front-end as shown in Fig. 6. A generic low-IF receiver is used to demon-

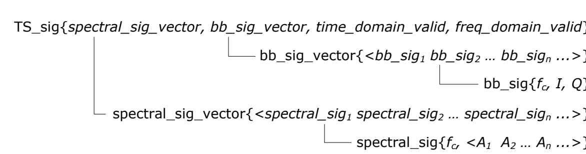

Fig. 5. SystemC user defined data type

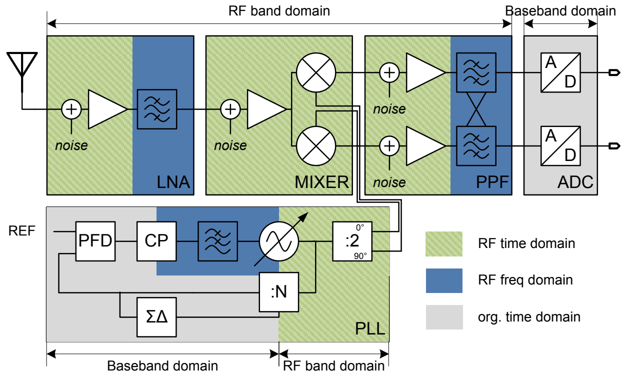

Fig. 6. Mixed-domain modeling of RF frontend

strate the reciprocal mixing caused by using the PLL signal as a local oscillator signal. This scenario is also one of concerning test case for other simulation methods like harmonic balance or PSS. The input of the front-end is a wanted sinusoidal signal at $f_c + 1\text{MHz}$ and an interference sinusoidal signal at $f_c + f_{ref} + 1.2\text{MHz}$. The reciprocal mixing resulting spectrum is shown in Fig. 7, while the output spectrum of PLL is shown in Fig. 8. These spectrums are converted from time domain simulation results.

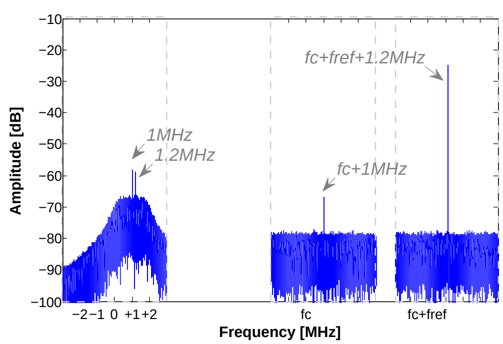

Fig. 7. Spectral components due to reciprocal mixing

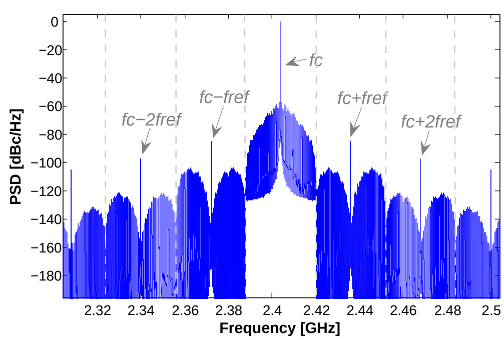

Fig. 8. Spectral components of PLL output

The generation of the PLL signal is shown in Fig.9 from CP to VCO. A loop filter is modeled in frequency domain, the spectrum resolution is determined by the length of FFT/IFFT. This length is also affecting the simulation speed. The choosing of this length is equivalent to the trade-off between simulation accuracy and efficiency.

In the aspect of the simulation efficiency, this modeling method is compared with the simulation of this RF front-end using original time domain passband signal abstraction

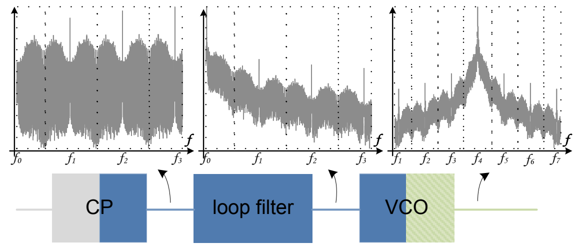

Fig. 9. Signal spectrum inside PLL

in Table I.

| | passband | mixed-domain |
|---|---|---|
| Front-end | $51s/1ms$ | $4s/1ms$ |
| PLL | $216s/1ms$ | $59s/1ms$ |
| Overall System | $1620s/1ms$ | $156s/1ms$ |

TABLE I
COMPARISON OF SIMULATION SPEED

## V. Conclustion

The HDL based behavioral modeling method is currently one of the most preferred solutions to speed up the simulations for RF system functional verification. Because of its flexibility, the behavioral modeling method can nearly cover all corners of wireless SoC. The evaluation of one behavioral modeling method consists of three aspects: simulation speed, modeling accuracy, and handcraft effort. The mixed-domain modeling method proposed in this paper brings in a big enhancement in simulation speed while keeping the models accurate enough for functional verification. Through domain conversion and signal abstraction switch, the manuall effort is saved by simplifying specific behavior descriptions in certain scenarios.

## VI. Aknowledgement

This work is supported by BMBF project ANCONA, which is sponsored by Germany Federal Ministry of Education and Research.

## References

[1] R. Rutenbar, G. G. E. Gielen, and J. Roychowdhury, "Hierarchical Modeling, Optimization, and Synthesis for System-Level Analog and RF Designs," *Proceedings of the IEEE*, vol. 95, no. 3, pp. 640–669, 2007.
[2] *SpectreRF User Guide*, Cadence Design Systems, 2005.
[3] K. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain," *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on*, vol. 5, no. 4, pp. 521–535, October 1986.
[4] H. Chang and K. Kundert, "Verification of Complex Analog and RF IC Designs," *Proceedings of the IEEE*, vol. 95, no. 3, pp. 622–639, 2007.
[5] J.-E. Jang and et al, "True event-driven simulation of analog/mixed-signal behaviors in SystemVerilog: A decision-feedback equalizing (DFE) receiver example," in *Custom Integrated Circuits Conference (CICC), 2012 IEEE*, 2012, pp. 1–4.
[6] J. Chen. Modeling RF Systems. [Online]. Available: http://www.cktsim.org/modeling/modeling-rf-systems.pdf