An Integrated Simulation Environment for Design and Analysis of Mobile Communication Systems

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ABSTRACT

In this paper we discuss the development of a simulation environment for the analysis and design of RF communication systems from the link level down to the nonlinear circuit level. The integrated simulation environment supports block diagram representations, multirate sampling, and an interactive graphical user interface. It enables the incorporation of sophisticated user models of individual blocks, in a mixed time-domain and frequency domain environment. The simulation of a multi-channel mobile communication system is presented. Large signal nonlinear distortion effects due to RF receiver front end such as harmonic distortion, intermodulation distortion and spurious noise are obtained using the integrated link level and circuit level simulation environment. Results of large signal effects on adjacent channel interference and signal-to-noise ratio are also presented.

I. INTRODUCTION

Many computer-aided analysis and design (CAAD) techniques have been developed in recent years to assist in modeling and testing of communication and signal processing systems [1]. Most of the work in this area focuses on performance evaluations and tradeoff analyses which are the central issues in the design of communication links and networks. Usually explicit performance evaluation of a system defies analysis and can be obtained only through digital computer simulation or prototype hardware evaluation. Indeed, hardware prototyping of many RF communication systems is still required to verify correct performance of analog subsystems. In contrast, digital circuitry can be adequately verified through digital computer simulations and the input-output relationships can be described algorithmically. An important issue remaining to be addressed in communication CAAD is the amalgamation [1] of several levels of a system into a single simulation package. Such a package should handle hierarchical top-down analysis and design of communication circuits, links, and networks [2]. Integrating link and circuit level simulation is essential as different layers of a system can strongly affect the performance of others and it is not always possible to isolate one part of a system from others.

The purpose of this paper is to present the design of a CAAD tool, integrating circuit level and link level simulation, for the simulation of mobile communication systems. The problem of estimating circuit level performance in the presence of many sources of impairments (such as inter- and co-channel interferences, up- and down-link noise etc. [3]) necessitated the design of an integrated simulation environment. The advantage of this simulation environment is its flexibility in interfacing other high level CAAD tools and its efficiency using mixed frequency domain and time domain processing. As an example a mobile communication system [4], including multiple transmitters, a physical transmission medium and a receiver, is simulated under large scale signal conditions in the presence of noise, adjacent channel interference, and intermodulation distortion.

II. CAAD SYSTEM DESIGN

Conceptually, the need for amalgamating the link level simulation with that of nonlinear RF circuits led to the design of an integrated communication system simulation environment. The main goal for this integrated environment was the development of a hierarchical approach to simulation which permits the use of multiple tools and a hierarchy within each level. A simulation tool at an intermediate level accepts data from the lower level models and provides data to the models used in the next higher level. By loosely integrating the simulation tools at successive levels in the hierarchy through a flexible interface, an integrated environment for simulation based analysis and design of communication and signal processing systems has been achieved.

The integrated simulation environment is a mixed time domain and frequency domain simulator. Time domain simulation is preferred for the analysis of digital signal processing elements and frequency domain simulation is preferred for the analysis of RF circuits. Furthermore, in RF communication systems, the baseband signal can be many orders of magnitude lower than the frequency of the RF signal. The usual approach in time domain link level simulators is to use complex envelope representations of signals and baseband equivalents of subsystems [5]. Simply increasing the sampling rate leads excessive amount of computation time. However, when we are dealing with nonlinear systems, the technique of baseband equivalents and envelope representation is inappropriate since nonlinear characteristics involved in the frequency translation from RF to baseband are not captured. We avoid these problems by simulating the RF circuits and transmission link entirely in the frequency domain. The CAAD tool we have developed can be divided into two parts: CAPSIM – a link level simulator, and FREDA – a nonlinear RF circuit level simulator.

A. LINK LEVEL SIMULATION : CAPSIM

CAPSIM [6] is an interactive simulation environment which supports a hierarchical definition of blocks and is a refinement and extension of BLOSIM [7]. A user supplied "topology definition" program specifies the name of the blocks, the routine which implements each block, the parameters used in each block, and how these blocks are interconnected. As in BLOSIM, each block used in CAPSIM is called a *star*. A block which is defined as a connection of other blocks is called a *galaxy* and the complete set of *stars* (or *galaxies*) that describes a communication system is called a *universe*. CAPSIM is essentially a

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time-driven simulator and each *star* is polled at each sampling instant. Multirate sampling techniques enable the simulation of many systems whose blocks have different bandwidths. The *stars* need not restrict their information transfer to waveform samples. A more complete description of CAPSIM is given in [6].

B. Circuit Level Simulation : FREDA

FREDA is a nonlinear RF circuit simulator and described in [8]. Although the methods for analyzing nonlinear RF circuits are varied, they are all based on solving a set of nonlinear differential equations resulting from the application of Kirchoff's voltage law and current law. The methods fall into three groups according to the way in which the nonlinear elements are treated: time-domain methods, hybrid (harmonic balance) methods, and frequency domain methods. Time domain methods analyze the nonlinear circuit by solving the nonlinear differential equations governing the circuit in the time domain using a method related to numerical integration [9]. They are generally regarded as unsuitable for RF and microwave circuit analyses as microwave and RF circuits typically have widely separated time constants in a set of stiff state equations. The consequence is that a small time step must be chosen and simulation proceeds for a large nubmer of time steps leading to excessive amount of computation time. Furthermore, it may be difficult to identify the steady-state solution when closely spaced frequencies are present. FREDA implements the harmonic balance and frequency domain methods of nonlinear RF circuit analysis [8]. Both methods implement spectral balance procedure as follows. A nonlinear circuit is partitioned into linear and nonlinear subcircuits as depicted in simplified form in Fig. 1. In this example the frequency domain form of the voltage v (i.e. a set of phasors) across both linear and nonlinear element is assumed and the current i (as a set of phasors) into the linear subcircuit is calculated using standard linear circuit techniques [9]. Then the current i' (again a set of phasors) flowing into the nonlinear circuit is calculated using the almost periodic Fourier transform technique [10], the multidimensional fast Fourier transform technique (NFFT) [11], or the arithmetic operator method (AOM) [12]. Of these, the NFFT method is preferred for the simplicity in nonlinear devise modeling and the AOM technique for speed and memory usage when there are two or more noncommensurable signals. Whichever method is used in determining the nonlinear current i', a balance of i and i' is achieved using a newton iteration scheme to update the estimated voltage v at the linear/nonlinear interface.

C. The Interface of Freda to Capsim

Now, we can proceed with the interface of FREDA to CAPSIM. As illustrated in Fig. 2, CAPSIM operates on a user defined topology which describes the system being simulated and defines the way *stars* are interconnected. Those *stars* which can be either user defined or system-provided are software programs written for the desired operation of a particular functional block. *Functions* (refer to Fig. 2), however, are specified routines to be called inside a *star* when they are needed. These functions can be Fast Fourier Transforms (FFT), digital filters, or any other user defined mathematical functions. FREDA is incorporated in CAPSIM as one of these functions to be used by *stars*. Therefore, once the simulation is executed according to the user defined topology, FREDA takes over as the nonlinear RF circuit simulator at the appropriate point in the simulation.

In summary, incorporation of the link level and the nonlinear circuit level simulation of the communication systems has resulted in a flexible integrated simulation environment which enables the designers to see the effects of link level perturbations on the nonlinear RF circuit level. In addition, filters and bandpass signals are represented in the frequency domain. Therefore inefficiencies introduced by high sampling rate are avoided.

III. Simulation Results and Discussion

The mobile communication system illustrated in Fig. 3 was examined for harmonic distortion, adjacent channel distortion and signal-to-noise ratio for a desired signal and an undesired interfering signal. The carrier frequency is at 900 MHz and the channel separation is 100 kHz. Therefore, the adjacent channel carrier frequency is at 900.1 MHz. The channel model used in the simulation is shown in Fig. 4. For the results presented, the channel attenuation has been changed to increase or decrease the received RF signal power. Typically, channel attenuation has been increased from 30 dB to 70 dB, for decreasing received RF signal power from -20 dBm to -60 dBm. The nonlinear RF circuit used in the simulations is a mixer illustrated in Fig. 5. The transmitted power from each transmitter has been kept constant at 6.25 Watts which is typical for medium range mobile radio [4] and the local oscillator power for receiver front end is 2.9 dBm (referred to 50 ohms) and the diode saturation currents are 30 pA. The transformers are virtually ideal. The IF spectrum is presented for the two-tone case with adjacent channel and additive white Gaussian noise are present in the system is presented in Fig. 6. Altogether there are 28 incommensurable (i.e. nonharmonically related) frequency components in this spectrum.

Harmonic Response

In the harmonic response curve, Fig. 7, the channel attenuation was changed from 35 dB to 110 dB which resulted in a received RF signal power variation between 0 dBm and 85 dBm. In this particular example, we only have a sinusoidal signal on the carrier. The first observation is the insignificant amplitudes for even numbered harmonics which is expected for the ring diode mixer as it produces only odd numbered harmonics [13]. Secondly, the nonlinear mixer circuit behaves linearly at small RF signal powers i.e., below 20dBm as expected. However as the RF signal power increases, the nonlinear characteristics are observed around -15 dBm received signal power. The third observation is the rapid decrease of power in higher order harmonics compared to lower order harmonics as RF signal power decreases which is as expected [13].

Noise Distortion

The SNR curve in Fig. 8 illustrates the response of the nonlinear RF mixer circuit to different values of RF signal power as channel attenuation changes. This measurement was obtained in the presence of additive white Gaussian noise. In this simulation, total RF noise power was kept constant at -68 dBm for a bandwidth of 100 kHz. IF noise power for the same bandwidth is -74 dBm. Therefore, the RF ring diode mixer introduces a conversion loss of 6 dB which is typical for such mixers [14]. The SNR curve is again linear at low RF signal power (below -25 dBm), i.e., the SNR increases at the same rate as RF signal power increases. However, around -20 dBm the curve bends showing the saturation effects in the mixer circuit.

Adjacent Channel Interference

The signal-to-adjacent channel interference ratio, SAR, curve in Fig. 9, presents the characteristics of the received signal power as the adjacent channel RF power changes. In this particular example, the desired signal is a two-tone signal at 20 kHz and 30 kHz and the adjacent channel, separated by 100 kHz, also has a two tone signal at 45 kHz and 55 kHz. Since inadequate filtering gives rise to leakage of power from the adjacent channel, significant power at frequencies 15 kHz, 25 kHz, and 35 kHz manifests itself as a result of adjacent channel interference. The SAR measurements were taken for various values of received RF adjacent channel interference. For this, channel attenuation for the adjacent channel has been varied while it was constant for the information carrying channel. In this curve the nonlinear characteristics are not observed clearly. The reason for this is that the leakage power only contains a portion of the received adjacent channel RF signal power. Therefore, it takes more power to drive the mixer circuit into the nonlinear region. Nevertheless, the nonlinear characteristics can still be observed around -25 dBm as the curve bends slightly.

Intermodulation Distortion

The two-tone intermodulation distortion test system presented in [15] has been simulated and the signal-to-intermodulation ratio curve, shown in Fig. 10, was obtained. In this simulation, we have only one channel carrying a two-tone signal. The intermodulation component is the difference of these two signals. Again we can notice the nonlinear characteristics around -25 dBm.

IV. Conclusion

The specific focus of this study has been the integration of link level simulation with circuit level simulation. For the simulation of a multi-channel mobile communication system we integrated a nonliner RF circuit simulator into the link level simulator. The integrated simulation environment is sufficiently flexible to enable the merging of other circuit level simulators. It has been shown that link level impairments such as noise and inadequate filtering can have significant effects on the nonlinear RF circuit level. The results clearly show that the integrated simulation environment which simulates both the link level and the circuit level was able to capture those effects such as harmonic and intermodulation distortion, noise and adjacent channel interference. Regions of linear and nonlinear operation were determined by the integrated simulation environment. The purpose of this simulation example was to verify the operation of the proposed integrated simulation tool: only by integrating a time domain link level simulator with a frequency domain nonlinear RF circuit simulator, is it practical to simulate the nonlinear large signal effects. Future work will investigate the effects of different modulation schemes in the transmitter and various RF nonlinear circuits in the receiver on overall link performance.

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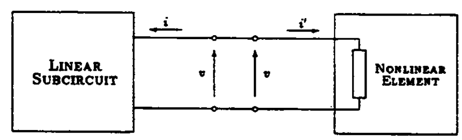
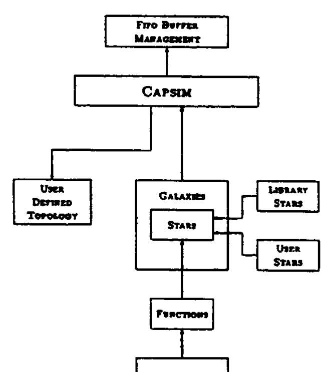


Figure 1



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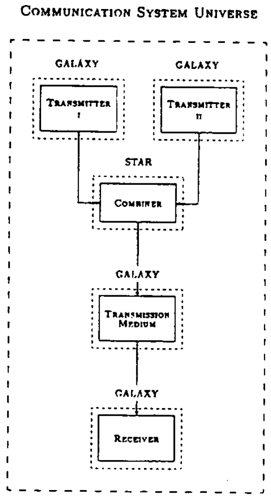

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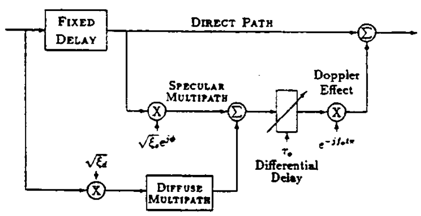

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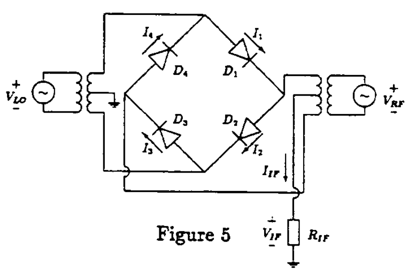

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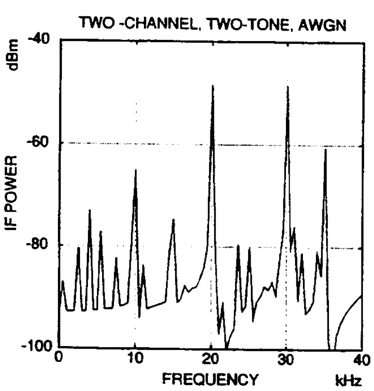

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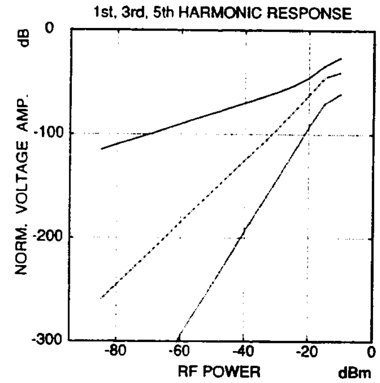

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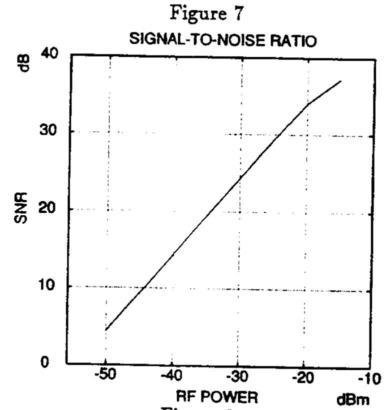

Figure 8

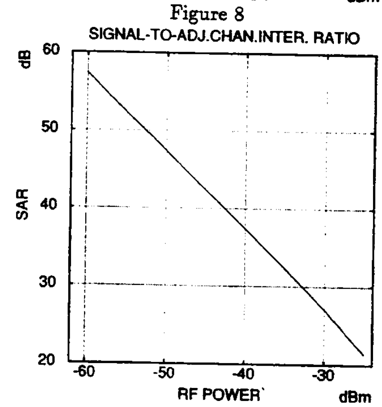

Figure 9

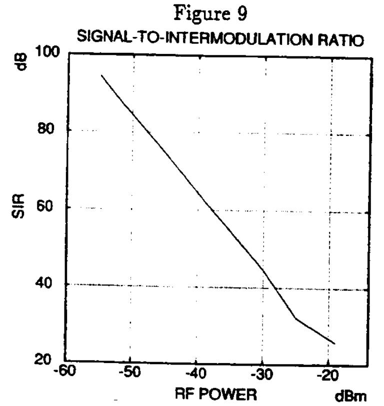

Figure 10