# Multilevel Simulation of WCDMA Systems for Third-Generation Wireless Applications

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## Abstract

Various types of RF/microwave CAD tools and techniques are described. We attempt to describe the relationship between various modeling/simulation techniques and describe their application during various phases of the engineering design process. We also describe the increasing importance of integrating various modeling methods and describe some approaches that have been made toward this goal and problems that have been encountered along the way. We illustrate the need for integrated simulation tools with a Wideband CDMA communication example.

## Introduction

Simulation techniques have been in use for many years to support the design and evaluation of electronic communication systems [1]. Over the past three decades, CAD techniques (including both computerized analytical techniques and simulations) have matured and are now usually applied at some point in the system design/development process. Impetus for the increased use of CAD techniques has stemmed largely from the growing intractability of the more complex systems now being fielded. Both systems and signal environments have grown more complicated with the advent of communication techniques such as spread spectrum modulation.

Code-Division Multiple Access (CDMA) techniques using Direct Sequence (DS) spread spectrum techniques were embodied in the IS-95-A cellular standard and are now the clearly accepted choice for third-generation cellular (3G) and PCS applications. The proposed 3G Wideband CDMA systems are complex in nature. This fact, coupled with the desire to operate these systems in concert with a diversity of systems employing other signaling formats seriously complicates the design process. CAD tools and techniques are being called upon more and more often to assist at different stages in the design.

## Simulation Tools and Techniques

The modeling and simulation process is often applied at different stages in the life cycle of engineering systems. Figure 1 illustrates a traditional view of those stages. At the conceptualization stage, simulation is typically used to explore "what if" scenarios involving tradeoffs of major design choices. In the design of wireless systems, the designer may need to select from various modulation schemes and/or error/control coding types to enable efficient transmission over a given channel. If a communication standard has already been specified, the designer might be tasked with developing an appropriate transceiver architecture for implementing the standard. This corresponds to the second level in the diagram. Both of these scenarios involve characterizing the system at the so-called "behavioral" level. At this level, we are interested in assessing the idealized behavior of the algorithms involved in the overall system design. This level of modeling is often called "system-level" modeling. End-to-end performance measures, such as Bit Error Rate (BER) are used to characterize system performance at this level. The next stage in the design cycle is the characterization of the non-ideal behavior of the various components and subsystems that will be used to physically implement the design. At this stage we are interested in designing the circuits which constitute both the RF and DSP portions of the design. The designer must assess the impact of various types of saturation, non-linearities, limited precision and a host of other practical issues that arise in a physical circuit. This level of design is usually called "circuit-level" design. Finally, modeling and simulation can be effectively used to characterize the performance of operational, or completed systems. It is often the case, for example, that new uses for old systems are proposed and simulation often is a cost-effective way to test an existing system under new operating conditions.

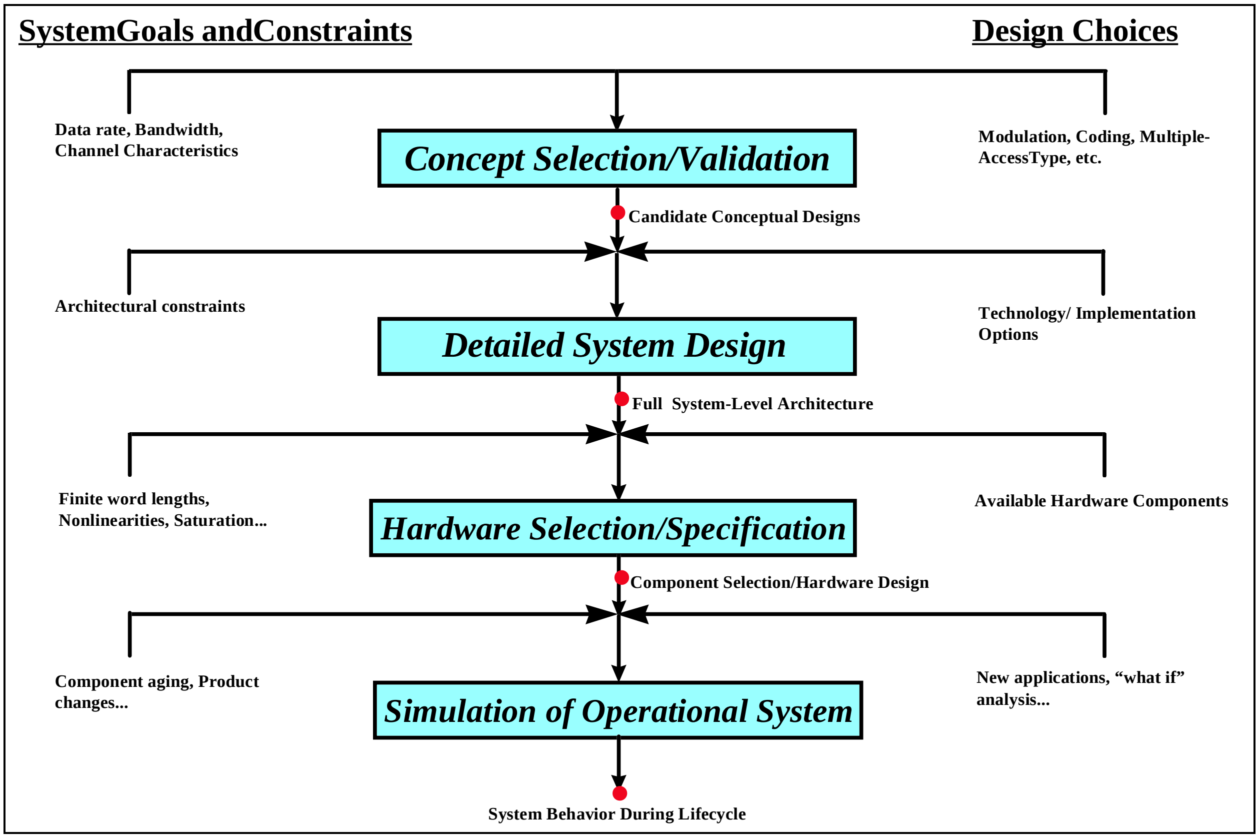

*Figure 1. Communication System Engineering Design Flow*

As stated earlier, the diagram in Figure 1 poses a "traditional" view of the engineering process, which is viewed as the "top-down" approach. One of the downfalls of this uni-directional design flow is lack of interaction between various parties involved in different stages of the design. This has become particularly troublesome between the "system-level" designers and "circuit-level" designers as more complex signal formats have had unforeseen effects on circuit components.

A combination of top-down and bottom-up design methodologies would foster a better integration of the labors of system engineers and circuit engineers. In many companies, these two groups have traditionally not interacted very much. They have often even been housed at different locations. This has resulted in unrealistic specifications being handed to circuit engineers and poor designs coming back. This usually results in engineers spending an inordinate amount of time answering the questions 'why doesn't it work?' and 'how can we patch it up?'. It is much better to be asking questions like how will mixer spurs affect the end-to-end Bit Error Rate (BER)' or 'how will amplifier non-linearity affect spectral regrowth of the signal' during the design process. This has become particularly important as more complex signal formats are being employed, such as CDMA.

Some progressive companies are now attempting to remedy this situation by better integrating the system and hardware design processes. Fostering an interaction between circuit and system engineers can result in streamlined design iterations and an efficient overall engineering process.

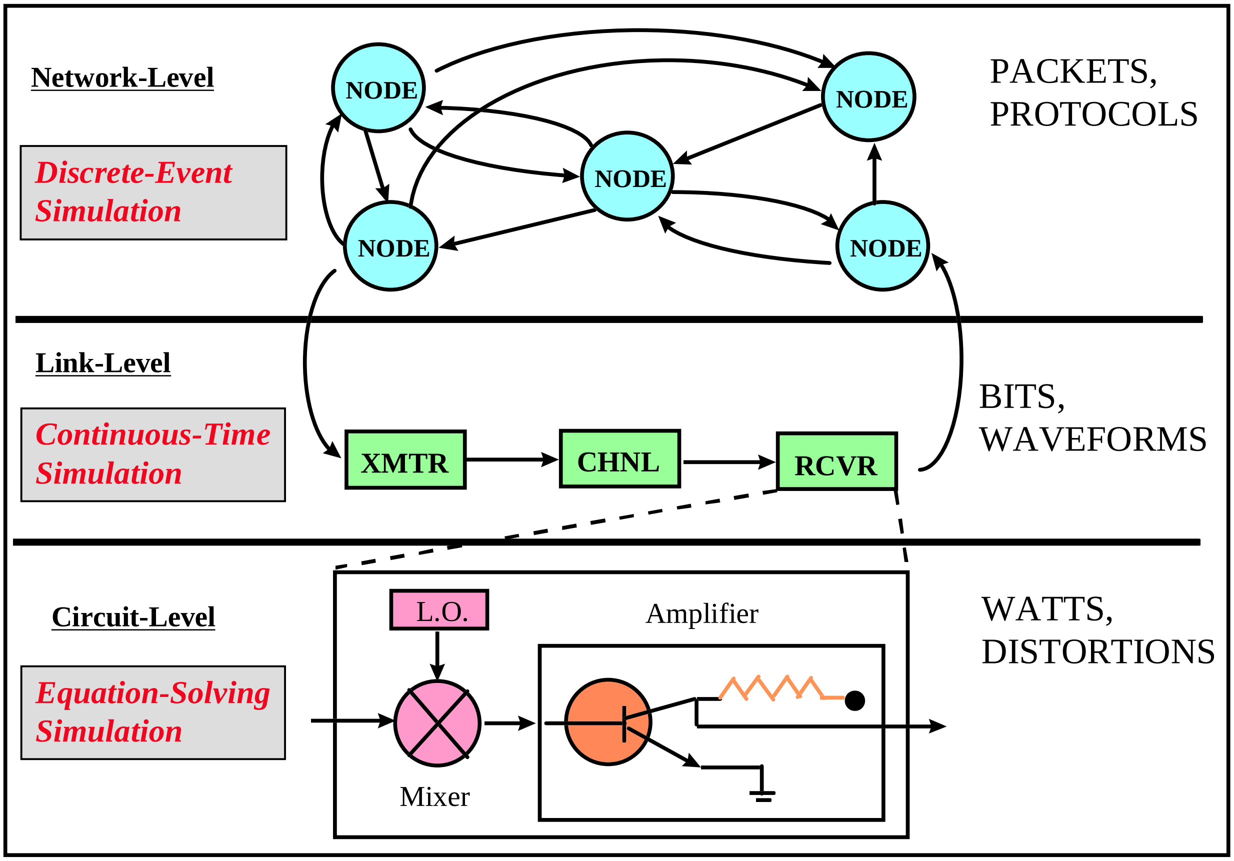

*Figure 2. "Communication System Modelling - Levels of Abstraction"*

Some the different types of modeling for wireless network design/development are shown in Figure 2. This figure attempts to categorize popular tools and techniques according to various levels of modeling abstraction. At the top level is network modeling and simulation. The communication simulation field has traditionally been divided into "network" and "link" simulation. At the network level, the user is interested in characterizing the aggregate of the data flowing between all of the various nodes in the communication network. While the size of the system model may be massive, the measures of performance are rather abstract. The interest at this level is to characterize the gross flow of traffic (typically packets) from point to-point in the network. Typical issues might involve the mean delay of a packet transmitted from Stockholm to London if it may have to traverse a number of hops. The probability of a packet error may be of interest. Because we are typically interested only in isolated events (i.e. packet generation, packet collision), we need not represent time as a continuum. A technique called "discrete-event simulation" is often employed at the network level to create efficient simulations of these isolated events.

At the "link" level, on the other hand, we are interested in characterizing all of the detailed signal processing taking place on a single transmission path, or a "point-to-point" system. Models are constructed of all of the components needed to process a time-varying waveform from the source all the way to the destination. In this type of simulation, the model must be able to predict the value of a time waveform at an arbitrary instant. This type of simulation is traditionally referred to as a "continuous-time" simulation. In most continuous-time simulations of communication links, a sampled-data approximation to analog waveforms is employed, again to create a run-time efficient simulation. This has the added advantage of allowing a link-level simulator to make use of traditional DSP techniques for approximating filters and other analog components. When the link contains components that are actually be implemented with DSP techniques, the simulation and the implementation agree more or less exactly. At the traditional link level, models are still primarily idealized, the simulation addressing mathematical algorithms, rather than the effect of non-ideal components.

Finally, at the circuit level, we are interested in characterizing the non-ideal behavior of the various subsystems and components that will be used to physically implement the design. This type of assessment necessitates the use of rather detailed models for both time-domain and frequency-domain analyses. Due to the presence of highly non-linear components, a simple sampled-data model is no longer appropriate for representation of signals and components. Sampled-data techniques rely on the fact that we know the limit of the frequency content of signals that are present at any point in the system. At the circuit-level, it is precisely this frequency content that we are trying to predict! Also, sampled-data techniques generally assume a uni-directional flow of data through a given subsystem or component. Circuit-level models must take into account two-way power transfers and are thus usually bi-directional in nature. As a result of these considerations, circuit-level simulation techniques usually involve establishing a set of circuit equations based on Kirchoff's current or voltage laws. This, in general, is a set of coupled non-linear differential equations that must be iteratively solved at individual time or frequency points. For time-domain analysis, SPICE-type programs solve the equations based on various strategies for linearization of the equations at each point in an ensemble of time instants. Harmonic-balance techniques involve solving non-linear equations on a set of frequency points. These techniques are accurate and powerful, but increase simulation run-time by of orders of magnitude.

## Multilevel Simulation

One way of bringing the system and circuit engineers together is through a common framework of design tools. This has been an ostensible goal of many CAD tool manufactures for over a decade. There has been modest success in the integration of system-level tools with DSP design tools, although the state-of-the-art is far from a seamless integration. Integration of system and circuit tools is still very much in its infancy, although much attention is currently being paid to this important issue. One of the major roadblocks to a full integration of the tools has been a difference in nomenclature between the system and circuit levels of modeling. For example, system-level engineers tend to be concerned with modulation bandwidth efficiency in terms of bits per second per Hertz. RF circuit-level engineers are concerned with exact placement of spurs in terms of absolute frequency. A circuit-level engineer must also be concerned with absolute power through a physical component, since manufacturers of mixers, amplifiers, etc. specify these parts on this basis. System-level engineers, on the other hand, are more concerned with signal-to-noise-ratio at the output of a receiver. These various aspects of a system are clearly related, but there exists much confusion about and even suspicion of an alternate perspective on the system specification. The remainder of this section specifically addresses some techniques that have been used to attempt to integrate system and circuit tools.

Multilevel modeling and simulation refers to any technique that allows the interaction of models operating at different levels of abstraction [2]. This may include such procedures as the import of the results of one simulation to act as input for another simulation. In a more complex case, it may involve the dynamic interaction of two simulations, with data being transferred between them as the simulations evolve. The term "co-simulation" has been applied to various types of data exchange between simulation models, although the definition of the term is not uniform within the industry.

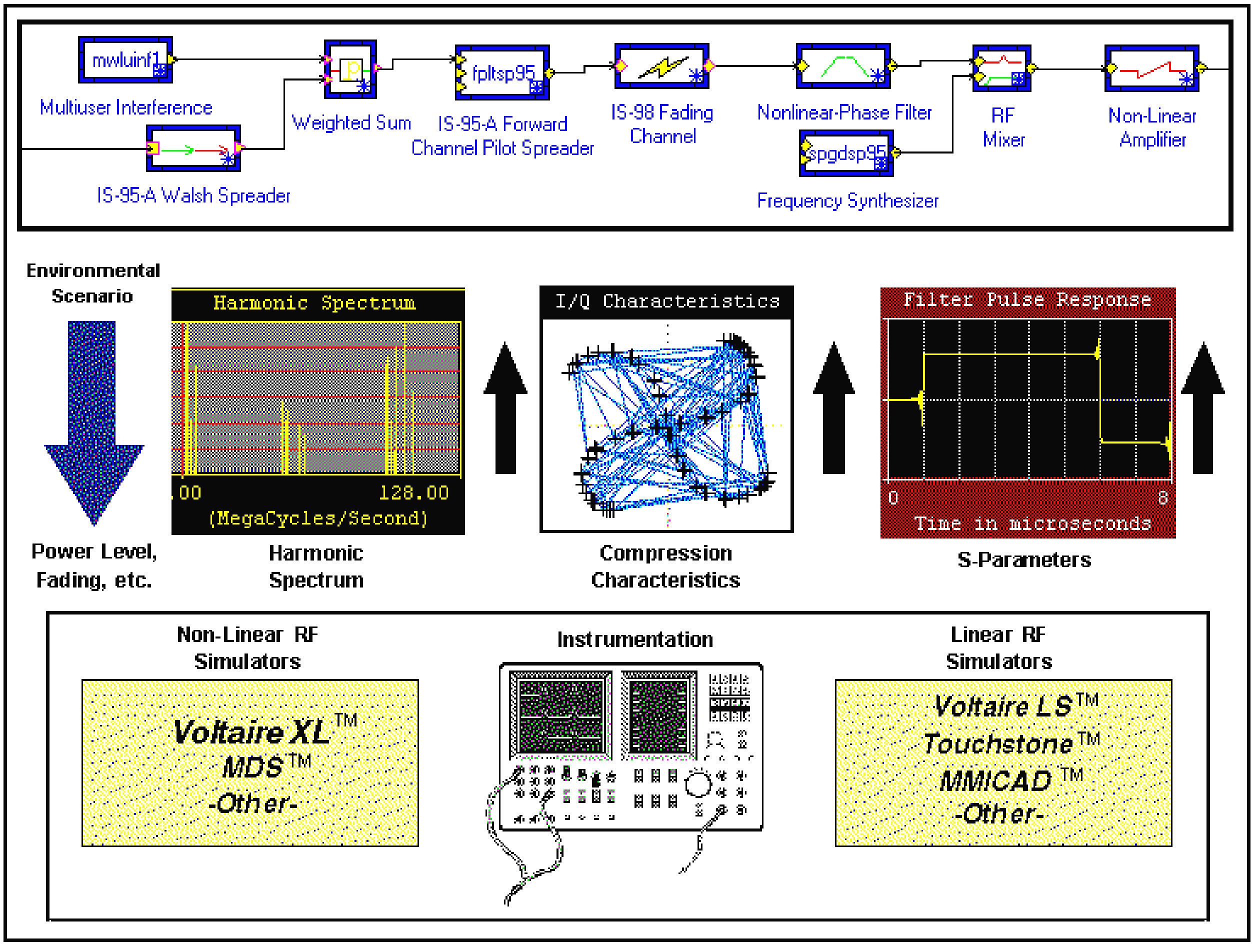

*Figure 3. Combined System-Level and Circuit-Level Modeling*

Figure 3 illustrates some of the types of data that can be shared between system-level and circuit-level simulations. A section of the screen image of a typical system-level simulation is shown in the top portion of the figure. Most system-level simulation tools now use block diagrams to represent the interconnection of various parts of a system model. Blocks represent models of processes and connections represent unidirectional flows of data between the various models. A simulation is created by generating a small segment of a sampled-data waveform (the limiting case is a single sample) and guiding it through each of the "model blocks" as they performs their respective operations. Useful information can be gleaned about the system operation by applying various probes and measurements at different points in the system topology. These techniques are standard and are embodied in many commercial simulation tools available today.

The particular system in Figure 3 has been chosen to illustrate some typical components where non-ideal behavior is a critical design issue.

Frequency mixers are used to implement frequency conversion, among other various uses. Most system simulators designed for RF systems employ complex-envelope representation of RF signals. By representing the inphase and quadrature (I/Q) envelopes of a narrowband signal, what is essentially a bandpass sampling may be emulated, which represents the spectrum accurately within the modulation bandwidth. This representation, closely related to the "zero IF" representation of a signal allows modest sampling rates for the representation of the signal. Unfortunately, complex envelope representation of an RF signal is not a complete representation of the signal and cannot fully represent all of the effects of non-linear elements in the signal path. In particular, not all harmonic components are generated that would be present if the real-world signals were passed through real-world non-linearities. Missing harmonic components may be identified using harmonic-balance or analytical prediction techniques, among others. These harmonic components may be injected back into the complex-envelope model in order to provide an accurate simulation of the effects of the non-linearities. A typical harmonic spectrum is illustrated in the left portion of the figure. It should be noted that the solution for the harmonic spectrum is essentially a steady-state solution, being derived from frequency-domain models. This implies that the signal characteristics are changing slowly enough so that a "spectrum" can be reasonably defined. Great caution must be exercised to ensure that this criterion is met.

Power amplifiers may be grossly characterized by their "compression" characteristics, usually including both amplitude and phase non-linearities. AM-to-AM and AM-to-PM characteristics may be derived from circuit simulation tools as well as laboratory instrumentation, such as a network analyzer. This is illustrated in the middle portion of the figure. A phase trajectory plot shows the distortion in the envelope of a signal as it is driven into saturation.

A third type of data that is often exchanged between circuit-level and system-level tools is S-parameter data. S-parameters, or "scattering" parameters describe the frequency-domain response of a system in terms of amplitude and phase as a function of the frequency of a single-tone stimulus. At the circuit level, bidirectional coupling and reflections are normally modeled, so that there are four sets of S-parameters for any two-port device. At the system level, only input-to-output transfer characteristics are modeled, so the input-to-output or S21 parameter is used. S-parameters are defined only for linear systems. The usefulness of S-parameters are predicated on the fact that there is a direct mathematical relationship between the frequency response of a linear system and its time-domain response. They are related through the Fourier transform. Given either representation, the response of the system to an arbitrary input may be determined. Given an arbitrary amplitude/phase response, a digital filter may be synthesized using well-known CAD techniques that can closely emulate the behavior of the real-world component.

These techniques for multilevel simulation are not the only ones that have been used, but these are the techniques that have been most widely used and have proven the most helpful. As the figure indicates, some data from a system-level simulation may be used as input to the circuit level. The types of data that are typically involved relate to power levels of various signals as a function of time. Again, if a frequency-domain analysis is performed at the circuit level to create the input data for the system level, great care must be taken that the signal characteristics are sufficiently slowly changing to permit a valid frequency-domain analysis.

One of the challenges facing the CAD industry is providing tools that are accessible simultaneously to both the system engineering and circuit engineering community. To date, these tools do not exist, but access to separate circuit/system tools is now being offered within some tool environments. An environment that is truly friendly to both communities would allow joint modeling of system and circuit aspects in a way that would be understandable and usable by both. This type of environment would allow both top-down and bottom-up design. Both are desirable to effect efficient iteration of designs.

## WCDMA Example

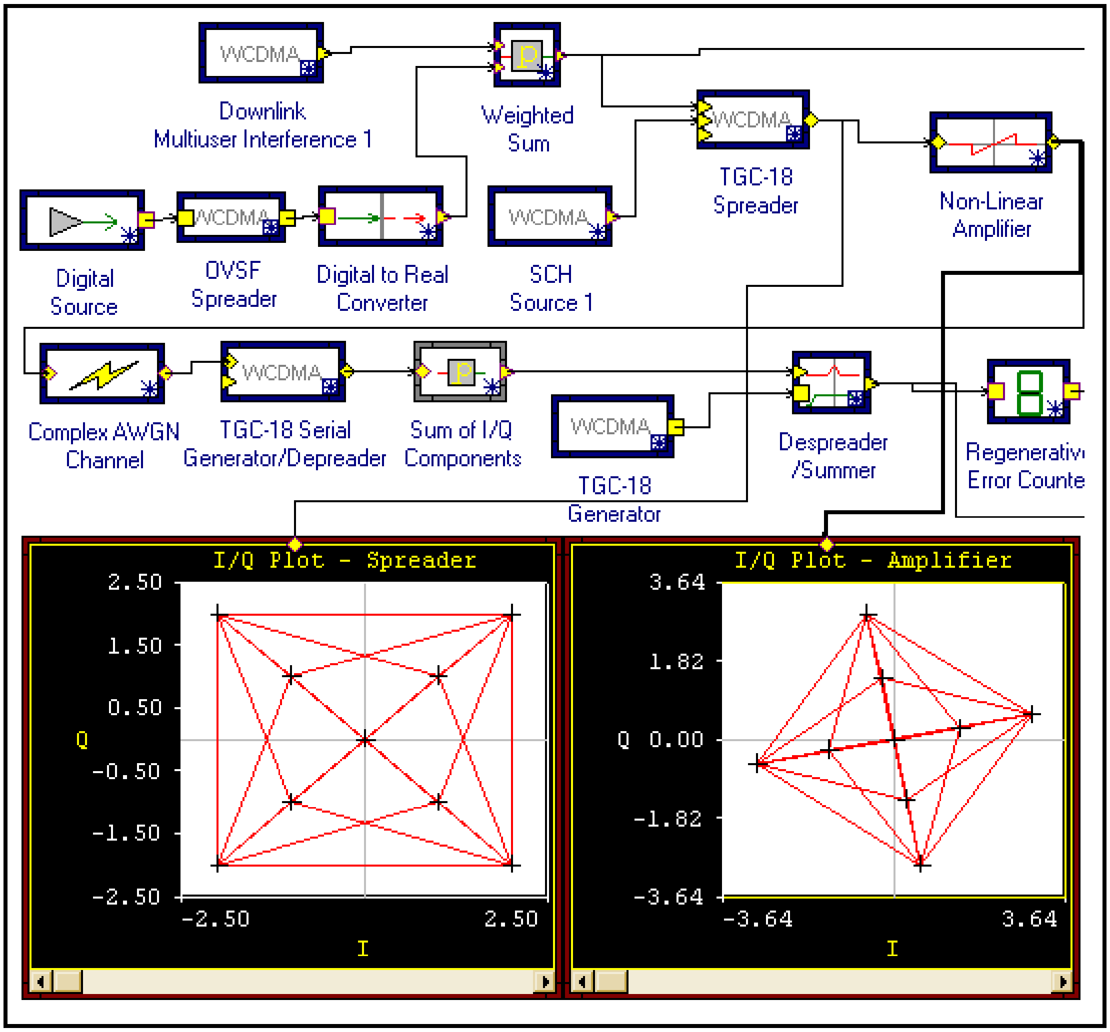

*Figure 4. Wideband CDMA Example - Single User*

In this section we present an example where a combination of system-level and circuit-level modeling is necessary. Both levels of abstraction are necessary to effect an adequate evaluation of certain critical system performance aspects. Figure 4 displays a screen image of a very simplified end-to-end WCDMA simulation. The goal of this experiment is to assess the effect of a non-linear amplifier on the BER of the direct-sequence signal. The model is based on the European UMTS W-CDMA proposal and incorporates models for the Synchronization CHannel (SCH), the Common Control Physical CHannels (CCPCH) and the dedicated channels (DPCH) [3]. The CCPCH and DPCH are code-division multiplexed with length 64 orthogonal codes. This is an intermediate value of spreading factor within the range of the proposal, (4-256). It also agrees with the orthogonal spreading factor of the IS-95-A standard. The example in Figure 4 is designed to asses the BER performance of a single orthogonal data channel. A random bit generator is employed to provide a source of data. The effect of multi-user interference is simulated by stimulating the orthogonal channels with random data. The multi-user interference may be turned on and off at a summing junction, implemented with a "weighted sum" model block.

Spreading by a truncated Gold code is performed after the desired orthogonal channel and the other orthogonal channels are linearly combined. The SCH is not orthogonal to the other channels, but is linearly added to their combination with a following "weighted sum" model block. No attempt is made to perform pilot, power, frame or code synchronization. Instead, perfect estimates of these values are employed at the receiver. The receiver consists employs a simple code despreading operation, first for the Gold code, then the desired user's orthogonal code. Chips are added across the code symbol to regenerate the original data, which are then compared against the transmitted sequence. A "regenerative error counter" model performs this operation by regenerating the transmitted sequence internally. A non-linear amplifier model, based on the AM-to-AM and AM-to-PM characteristics described in an earlier section is employed before an AWGN transmission channel. Figure 4 displays the ideal and distorted phase trajectories at the input and output of the non-linear amplifier. The multiuser interference is turned off in this simulation run. In this figure, the shape does not change very much, as the amplifier is not operating close to saturation.

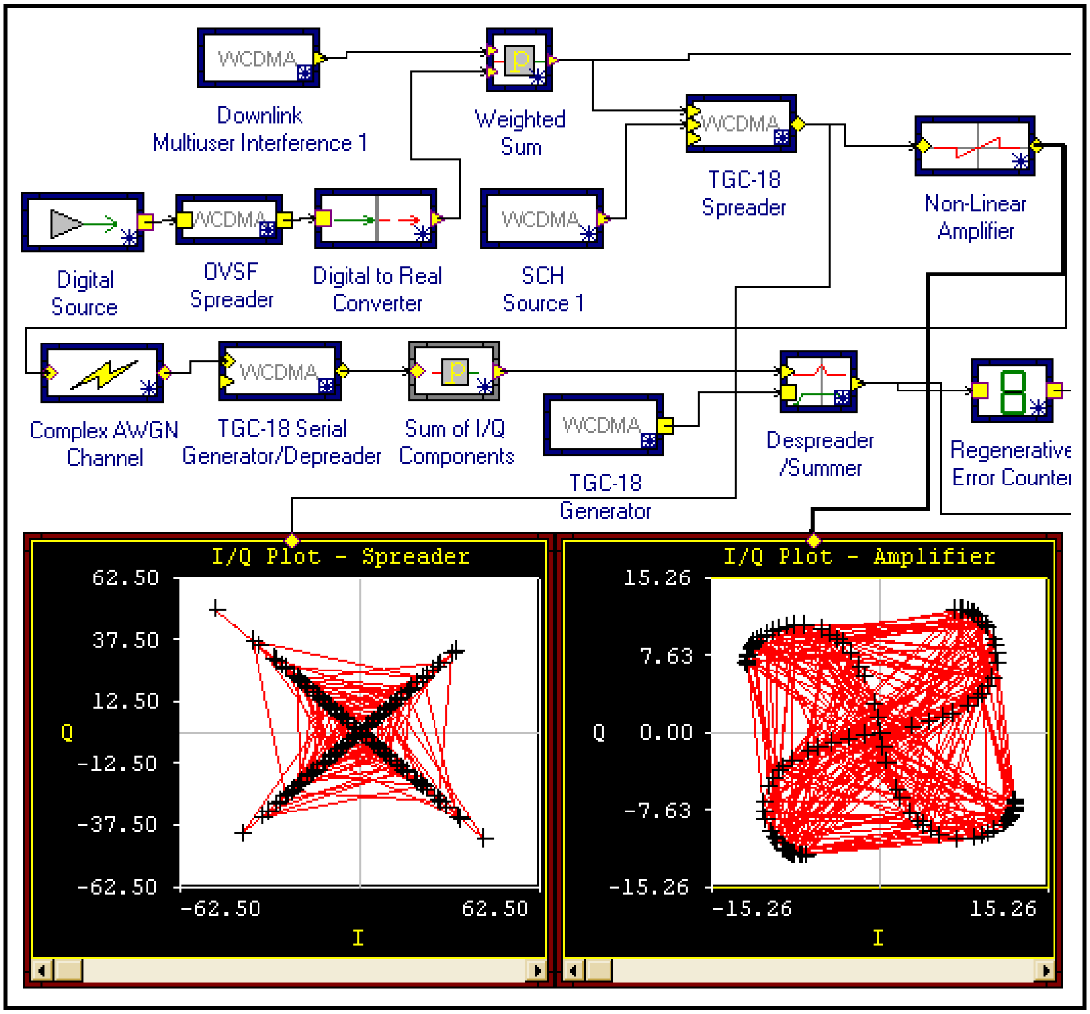

*Figure 5. Wideband CDMA Example - Multiple Users*

Figure 5 illustrates the case when the multiuser interference is turned on. The model parameters are adjusted so that all orthogonal channels are active and transmit continuously. This is admittedly an extreme case, with the amplifier output phase trajectory showing significant distortion. The amplifier is biased in both cases to reflect the same average backoff point. Due to the addition of the multiple spreading codes, the signal has a very high dynamic range, causing the amplifier's peak output value to be driven well past saturation.

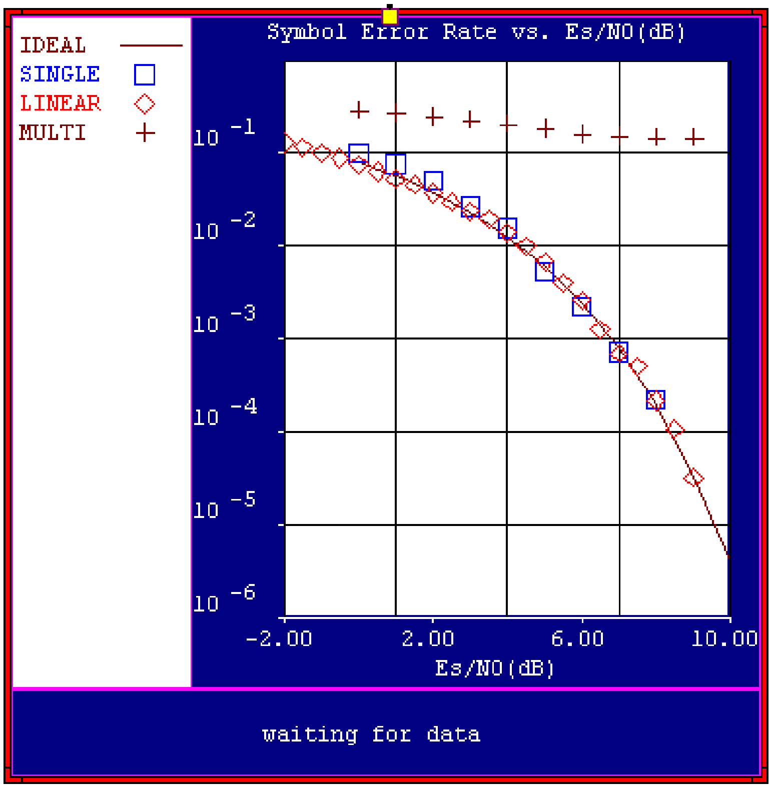

*Figure 6. BER for Wideband CDMA Example*

BER curves are illustrated in Figure 6. A calibration run for the linear case (no amplifier in the signal path) is shown in diamonds, superimposed on the theoretical result for antipodal signaling in AWGN. The performance with the non-linear amplifier with only the desired signal active is shown in squares. Note that the presence of the SCH channel does not significantly affect the BER results, since the SCH signal is randomized (but not orthogonalized) at the receiver.

The BER curve representing the performance with the amplifier is shown in crosses. As expected, the performance of the system is essentially destroyed due to the distortion in the amplifier. This result indicates that a highly linear amplifier may be needed to maintain signal fidelity. Exact BER results will depend on the amplifier characteristics and the statistics of the user traffic in a complex way. Simulation provides the only means of realistically assessing the system performance under these varying conditions.

## Conclusions

In this paper we have attempted to provide motivation for the use of multi-level modeling techniques to support the design and analysis of 3g systems. Complexities of new systems and signal formats are necessitating the use of combined circuit-level and system-level simulation tools and methodologies to fully evaluate end-to-end system performance.

## References

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