A Software Simulation Testbed for Third Generation CDMA Wireless Systems

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Abstract

This paper describes a testbed which simulates a third generation Code Division Multiple Access (CDMA) wireless link. The designer of next generation wideband CDMA systems has the choice of a wide array of advanced signal processing algorithms and a variety of operating environments. The Rice testbed is a tool to evaluate these design options and trade-offs in different system scenarios.

The backbone of this testbed is a wireless CDMA multiuser link built using Simulink and Matlab. An efficient method of system modeling is used to accelerate the simulations. The testbed also uses a method for rapid prototyping of algorithms and DSP-based simulation acceleration for new algorithm complexity and performance evaluation.

1 Introduction

Wireless cellular networks are growing at a tremendous rate driven by demand in wireless services and improvements in access schemes. The push for better usage of available RF bandwidth has driven the research in developing new signal processing algorithms for different components of the system. The developments in the physical layer receiver structure have been in channel estimation and multiuser detection (which extract the bits from the baseband signal from the channel), and in the source and channel coding schemes (which make efficient use of available bandwidth and protect against errors). These schemes are primarily targeted at the evolving standards like CDMA2000 and UMTS for third generation (3G) wireless systems which use Wideband CDMA (W-CDMA) as the access method [9, 11].

The testbed simulates a multiuser direct sequence CDMA link (Figure 1) using the Simulink and Matlab environment. The second section motivates the need for a simulation testbed for wireless systems. The third section presents the development of the W-CDMA wireless testbed in simulink software. The fourth section details the features of the testbed, the fifth section presents a prototyping and simulation acceleration methodology developed using the Real-Time workshop tool and the final section summarizes the work.

2 The Need for a Simulation Testbed

A wide range of advanced signal processing algorithms and system configurations are available for designing a future cellular communication network. The simulation testbed allows the evaluation of the design choices in systems based on 3G W-CDMA standards [9, 11]. Other variables such as the properties of the channel, which are affected by environmental factors are included in the simulations. A complete algorithmic evaluation needs to consider all such factors. The simulation testbed is envisioned to have the following capabilities [10]:

A comprehensive method of algorithm evaluation: The typical method of evaluating a new algorithm, by doing a localized simulation, does not provide accurate insights into the algorithm behavior in a real system. The CDMA wireless testbed aims at providing an environment which models all facets of a real wireless system and provides a complete picture of system behavior with various algorithms.

Algorithm trade-off issues: The algorithmic choices for each block differ in the computational complexity and in the resulting performance. The W-CDMA testbed is intended to assist in the choice of an algorithm.

Generation and analysis of performance indicators: The transmission of long bit-streams through a W-CDMA system is simulated and the errors in the received bit-stream are counted. The performance of the system is quantified using the average *bit error rate (BER)* and *frame error rate (FER)*.

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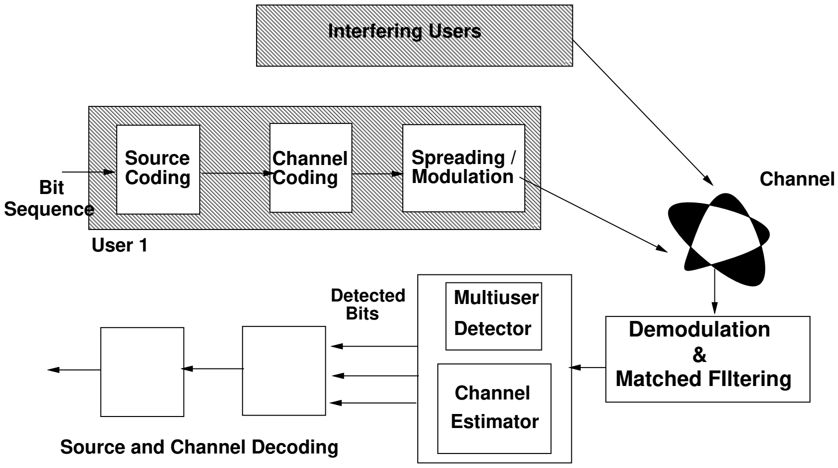

Figure 1. A Multiuser W-CDMA Baseband Wireless Link

Utilization of DSP hardware: Digital Signal Processors (DSPs) are well suited for signal processing in communication applications and are extensively used in developing products like cellular phones and base-stations [1, 6]. The simulation testbed is intended to be used as a platform to test the use of DSPs in CDMA systems using hardware/software co-design tools including RTW from Mathworks [2].

3 Construction of the W-CDMA Testbed using Simulink

The simulation testbed is built as a Simulink block diagram [2] shown in Figure 2. The different components for the system (Figure 1) are obtained from different libraries. A Simulink block diagram can use blocks from the standard libraries or custom libraries with models defined using S-functions (Simulink-functions). The S-functions can be written as Matlab files or C-MEX ('C'-Matlab EXecutable). Simulink is useful as a *wrapper* for existing Matlab and 'C' code fragments. Many of the S-functions are modified from *legacy* code used for earlier evaluations.

The W-CDMA link uses a system of asynchronous transmissions, a multipath AWGN channel, and an advanced receiver structure. The front end of the multiuser receiver consists of a chip matched filter which discretizes the baseband waveform and uses it for channel estimation and detection.

Consider a Direct Sequence CDMA system with K users and a short repeating spreading code with N chips per bit. BPSK modulation is used with each transmitted signal limited to $[0, T]$. The received signal due to the superposition of the attenuated and delayed signals of the K users is

$$r(t) = \sum_{k=1}^{K} w_k \times \sqrt{2P_k} \sum_{i=0}^{L-1} b_{k,i} \times c_k(t - \tau_k - iT) + \nu(t), \tag{1}$$

where P_k is the transmitted power of k^{th} user; $b_{k,i} \in \{+1, -1\}$ is the i^{th} transmitted bit in a stream of L bits; w_k is the complex amplitude of the k^{th} signal due to the effect of channel attenuation and the phase offset; τ_k is the relative delay with respect to a reference at the receiver. The noise component $\nu(t)$ is assumed to be Gaussian with zero-mean and double-sided spectral density of $\mathcal{N}_0/2$. This received signal is fed into a chip matched filter whose output is

$$r[n] = \int_{nT_c}^{(n+1)T_c} r(t)dt. \tag{2}$$

A discrete observation vector $\mathbf{r}_i$ is formed at bit i by sampling the integrator output and collecting N successive chip matched filter outputs:

$$\mathbf{r}_i = [\ r[i] \quad r[i+1] \quad \cdots \quad r[i+N-1]\ ]^T. \tag{3}$$

Each observation vector $\mathbf{r}_i$ can be viewed as a linear combination of $2K$ signal vectors, corresponding to 2 from each of the K users due to the past and the current bits. So $\mathbf{r}_i$ can be written as

$$\mathbf{r}_i = \mathbf{AWb}_i + \nu_i, \tag{4}$$

with $\nu_i \sim \mathcal{N}(\mathbf{0}, \mathbf{K})$; $\mathbf{A}$ is the $N \times 2K$ matrix of signal vectors, which depends on spreading codes and delays of each of the users; $\mathbf{W}$ is a $2K \times 2K$ diagonal matrix of complex amplitudes; $\mathbf{b}_i$ is the $2K \times 1$ vector of the K users' previous and current data bits; and the $N \times 1$ vector $\mathbf{K}$ is the noise covariance.

The channel estimate is obtained using a maximum likelihood type method [4, 8, 7]. The channel estimate (including the delay and amplitude response) is available as the product of the effective spreading matrix and channel impulse response matrix, from which the cross-correlation matrix can be derived and used in the multiuser detector for interference cancellation. Multiuser detection [3] can be

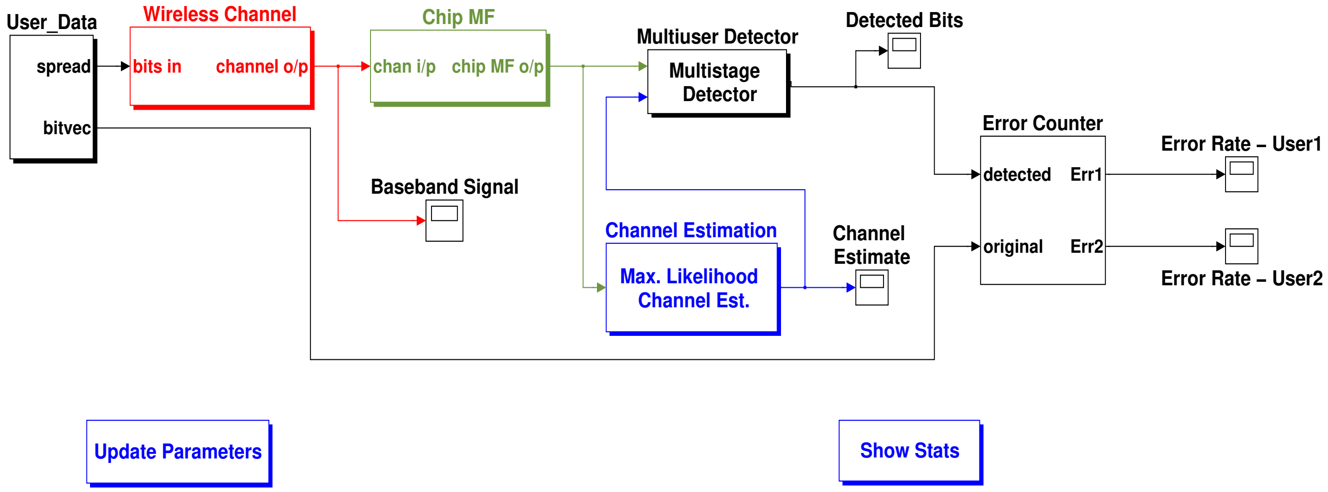

Figure 2. The Software (Simulink) W-CDMA Testbed

implemented using schemes such as Decorrelation, Differential Multistage [3, 12, 13]

The channel parameter estimation method uses a fixed preamble which is known at the receiver. The preamble bits are initially transmitted through the channel and the discretized received signal from the channel is used to estimate the channel parameters (amplitude, phase, and delay information).

The equation for the received chip matched filter output 4 is re-written as in the equation 5. This method accommodates the effects of multiple paths without increasing the size of the matrices $\mathcal{U}$ and $\mathbf{Z}$, but making them more dense [4, 5, 8].

$$\mathbf{r}_i = \mathcal{U}\mathbf{Z}\mathbf{b}_i + \nu_i, \tag{5}$$

where $\mathcal{U} = [\mathcal{U}_1^R \ \mathcal{U}_1^L \cdots \mathcal{U}_k^R \ \mathcal{U}_k^L \cdots \mathcal{U}_K^R \ \mathcal{U}_K^L]$ and $\mathbf{Z} = diag(\mathbf{z}_1, \mathbf{z}_1, \cdots, \mathbf{z}_K, \mathbf{z}_K)$; with $\mathcal{U}_k^R = I_M \otimes \mathbf{U}_k^R$ and $\mathcal{U}_k^L = I_M \otimes \mathbf{U}_k^L$; the operator '$\otimes$' represents the Kronecker product of two matrices and I_M is the M dimension identity matrix; Further $\mathbf{U}_k^{(R)} = [\mathbf{c}_k^{(R)}[0] \cdots \mathbf{c}_k^{(R)}[N-1]$ and $\mathbf{U}_k^{(L)} = [\mathbf{c}_k^{(L)}[0] \cdots \mathbf{c}_k^{(L)}[N-1]]$ are the matrices formed from the spreading codes delayed by all possible integer delays. For the single sensor case considered here,

$$\mathbf{z}_k = \begin{bmatrix} 0 \\ \vdots \\ w_{k,1}(1-\gamma_{k,1}) \\ w_{k,1}\gamma_{k,1} \\ \vdots \\ w_{k,P}(1-\gamma_{k,P}) \\ w_{k,P}\gamma_{k,P} \\ \vdots \\ 0 \end{bmatrix}. \tag{6}$$

It is shown in Sengupta's work [4, 8] that the channel parameters extracted using Maximum Likelihood estimation can be captured in a single matrix $\mathcal{Y} \triangleq \mathcal{U}\mathbf{Z}$. This matrix is estimated as $\widehat{\mathcal{Y}}$, where

$$\widehat{\mathcal{Y}} = \widehat{\mathbf{R}}_{rb}\widehat{\mathbf{R}}_{bb}^{-1}, \tag{7}$$

and

$$\widehat{K}(\widehat{\mathcal{Y}}) = \widehat{\mathbf{R}}_{rr} - \widehat{\mathcal{Y}}\widehat{\mathbf{R}}_{rb}^H, \tag{8}$$

with $\widehat{\mathbf{R}}_{rr} = \frac{1}{L}\sum_{i=1}^{L}\mathbf{r}_i\mathbf{r}_i^H$, $\widehat{\mathbf{R}}_{br} = \frac{1}{L}\sum_{i=1}^{L}\mathbf{b}_i\mathbf{r}_i^H$, and $\widehat{\mathbf{R}}_{bb} = \frac{1}{L}\sum_{i=1}^{L}\mathbf{b}_i\mathbf{b}_i'$. Further, the estimate of this matrix $\mathcal{Y}$ can be used to find the matched filter detector output vector $\mathbf{y}_i$ using

$$\mathbf{y}_i = (\mathcal{U}\mathbf{Z})^T\mathbf{r}_i, \tag{9}$$

where $\mathbf{r}_i$ is the chip matched filter output vector. Further, the $\mathcal{U}\mathbf{Z}$ matrix can be used to generate the cross correlation matrix $\mathbf{R}$ using

$$\mathbf{R} = (\mathcal{U}\mathbf{Z})^T(\mathcal{U}\mathbf{Z}). \tag{10}$$

The basic **Matched filter** detector, correlates the received waveform with the suitably delayed version of the spreading code. It does not cancel the effect of interference from other users. The detected bits are

$$\hat{\mathbf{d}} = \mathbf{y} = \mathbf{R}\mathbf{A}\mathbf{d} + \nu, \tag{11}$$

where $\mathbf{y}$ is the K chip matched filter vector; $\mathbf{R}$ is the $K \times K$ correlation matrix obtained from the channel estimate; $\mathbf{A}$ is the $K \times K$ amplitude matrix; $\mathbf{d}$ is the K vector of data bits and ν is the noise vector.

The software testbed has a choice of two **Multiuser detection** schemes. The **Decorrelator** is a linear detector [3], which applies a linear transformation to the matched filter output to reduce the effect of multiple access interference(MAI). The transformation $\mathbf{R}^{-1}$ is applied to the matched filter output $\mathbf{y}$ which eliminates MAI. So

$$\widehat{\mathbf{d}}_{decorr} = \mathbf{R}^{-1}\mathbf{y} = \mathbf{A}\mathbf{d} + \mathbf{R}^{-1}\nu. \qquad (12)$$

The **Differencing multistage:** is an efficient version of multistage detectors which use a (non-linear) parallel interference cancellation technique [12]. The multistage method removes the necessity to calculate the inverse of $\mathbf{R}$, by using an iterative method to successively cancel the interference. In multistage detection, the l^{th} stage of the detection is

$$\widehat{\mathbf{z}}^{(l)}_{multistage} = \mathbf{y} - \mathbf{R}\mathbf{A}\widehat{\mathbf{d}}^{(l-1)}, \qquad (13)$$

with

$$\widehat{\mathbf{d}}^{(l-1)} = sign(\widehat{\mathbf{z}}^{(l-1)}_{multistage}), \qquad (14)$$

where $\widehat{\mathbf{z}}^{(l)}_{multistage}$ is the soft decision estimate in the l^{th} iteration and $\widehat{d}^{(0)} = sign(y)$.

It is seen in a multistage detector that many of the consecutive hard decisions do not differ, especially in the later stages of convergence. The differencing multistage detector takes advantage of this factor and uses the differential between 2 successive stages l and $l-1$ instead of the soft decision in the l^{th} stage to save computations [13].

4 Features of the W-CDMA Simulation Testbed

The testbed (Figure 2) offers the advantages of modularity, scalability and efficient simulation. The use of Real Time Workshop also allows a way of prototyping algorithms on DSP hardware.

The Backbone of a scalable simulation testbed: The baseband multiuser link acts as the backbone for developing more complex systems. This flexible link has a graphical user interface which allows a system designer to test different scenarios by changing the parameters (such as number of users, paths, channel properties and spreading waveforms). We have developed a library of algorithms with blocks for different parts for the transmitter and multiuser receiver. The modular design of the simulation system allows easy addition of new algorithms to the library. Realistic channel models are being incorporated into the system.

An efficient method of simulation: The testbed uses a method of simulation which provides accurate simulation without requiring a very fine sampling granularity. In a real system the continuous time signal at the output of the channel is converted to a discrete time signal by sampling the output of a filter matched to the chip waveform (which is a rectangular pulse in our system). However, the simulation system models the channel output as a discrete time signal; hence the output of the chip matched filter has to be derived from this discrete time channel output (which is available as a finite number of samples per chip). The traditional CDMA *simulation* system has the minimum sampling time equal to a fraction of the chip duration. The use of a discrete channel output also introduces an error in the chip matched filter output, which can be abated by increasing the channel sampling rate. But an increase in the sampling rate slows down the simulation. We incorporate a novel method of combined spreading, channel modeling and matched filtering to obtain accurate results, while keeping the system sampling time to once a chip (Figure 3).

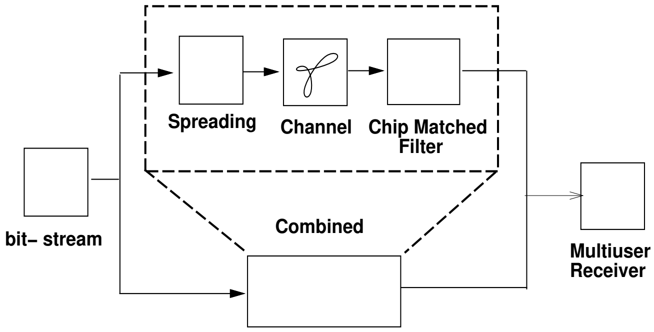

Figure 3. Two methods of baseband modeling

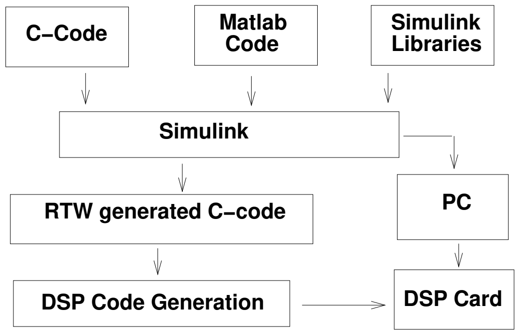

Figure 4. RTW based prototyping

5 Rapid prototyping using Real Time Workshop

DSPs are widely used in prototyping of signal processing algorithms and communication systems [1, 6]. Base-station and Mobile phone hardware for 3G systems will use DSPs for baseband processing of the receiver algorithms which were evaluated in the testbed. Hence it is useful to have a method of quick DSP prototyping of algorithms developed using the testbed.

Simulink has a component called Real-Time Workshop (RTW), which generates ANSI C-code [2]. The C-code can

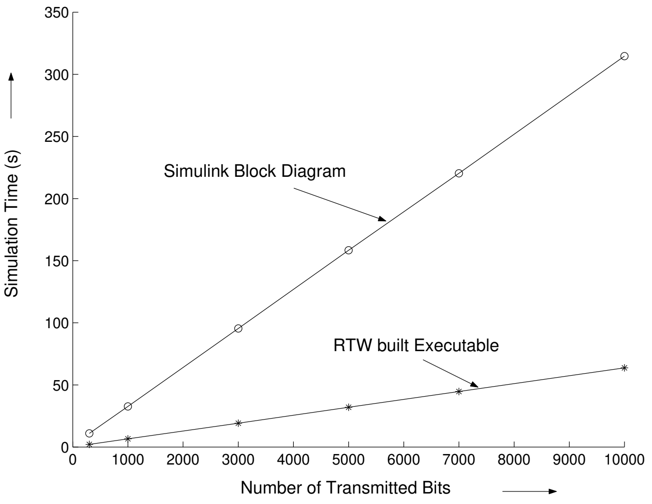

Figure 5. Simulation Time Comparison

be compiled using code generation tools for either the PC host or a DSP board. The executable derived from this process can run independently of the Matlab environment. The stand-alone simulations are faster than the Simulink block diagrams using the Matlab engine (which uses an interpreter to run the S-functions). This prototyping method shown in Figure 4 is used to acheive faster simulations on the Pentium host.

RTW based simulation system for the Pentium host: The complete W-CDMA physical layer link was also built using C-MEX code. The system used parameters which are in close conformance with emerging W-CDMA standards. The RTW tool was used to generate the C-code for stand-alone simulators for frame length data (of the order of 10000 bits) . This code was compiled and linked using Visual C++ tools to create a executable for the Pentium class host. This compiled simulator showed speed-ups of about 6 times the Simulink version with Matlab blocks (Simulation time vs. number of bits are plotted in 5).

DSP rapid prototyping: RTW is a tool for rapid-prototyping, i.e. quick translation of algorithmic ideas to DSP implementations. The Simulink block diagrams can be used to package some of the algorithms into commercially viable products. For example, the uplink receiver modeled in the testbed is the baseband section of a wireless base-station.

6 Summary

In this paper, we discussed the Rice W-CDMA testbed built using Simulink. The testbed is designed to be a flexible, modular simulation system for baseband algorithms used in 3G wireless systems. We also demonstrate Real Time Workshop based C-code generation for a complete multiuser baseband link. The executable generated for the Pentium host from this C-code runs significantly faster than the original simulation system. Further it is possible to use this generated C-code for rapid prototyping on floating point DSP hardware and for hardware in the loop (HIL) simulations. Such a method can be used for simulation acceleration.

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