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Description	

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Real-Time Simulation of Adaptive Array Antenna using Broadband Vector Channel Simulator

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Abstract

It has been well recognized that joint spatio-temporal signal processing is a key technology to fully exploiting multipath propagation in broadband wireless communication systems. Advanced wideband radio channel simulators and parameter estimators can reduce the costs of algorithm research, system design, and testing, and accelerate the development speed for new systems. This paper introduces a real-time simulation platform for adaptive array antennas. The system includes a broadband vector channel simulator and a systolic array parameter estimator that are connected and jointly operated.

Keywords

Radio channel simulator, multipath fading, systolic array, antenna array, parameter estimation, the RLS algorithm

1 INTRODUCTION

It is reasonable to set the bit rate targets for post-3G mobile communication systems higher than 3G's maximum speed, with the aim that *real* multimedia communications will prosper on post-3G networks. Given that the system bandwidth needed to meet broadband communication requirements may not be fully available, the post-3G networks will have to be resistive against co-channel interference (CCI). It is obvious that broadband signaling over mobile radio channels imposes severe inter-symbol interference (ISI) upon the received signals due mainly to the effect of multipath propagation. Hence, a technological breakthrough that can reduce the effects of CCI and ISI while taking full advantage of the benefits of multipath propagation is needed.

Unlike the 3G and prior systems, which mainly exploit the received signal's temporal structure, future broadband mobile communication systems must well exploit the received signal's temporal and spatial structures. In fact, the received signal's directional spread provides us with another dimensionality that can be used to resolve the received signal components, and then to recombine them.

Tremendous effort is currently being made to exploit the spatial dimension of channels. In this framework, the importance of real-time simulations of the spatial and temporal mobile radio channel structure has been recognized. Testing of post-3G system prototype should require simulator's bandwidth to be wider than the prototype's required bandwidth itself, which may reach several tens of MHz.

This paper is organized as follows: Section 2 introduces the system model for real-time simulation of adaptive array antenna systems. Section 3 describes major specifications of the spatio-temporal mobile radio channel simulator, "PROPSim C8", which features results of the most recent propagation research, and exploits state-of-the-art implementation technologies. The technological bases for increasing simulator bandwidth and enhancing amplitude, phase and delay adjustment/calibration accuracy are briefly described. Section 4 describes how PROPSim C8 can be used for the experiments of Spatio-Temporal (S/T) equalizers. In section 5, results of simulations and measurements conducted to verify PROPSim C8 performances are described. Section 5 also introduces a platform system for adaptive array antenna simulations, where a general purpose parameter estimator, "SPE4000", that performs the recursive least square (RLS) algorithm using a QR decomposition-based systolic array technique, is connected to PROPSim C8. The platform includes the desired and interference users' transmitters, PROPSim C8, a signal combiner, and SPE4000. PROPSim C8 simulates the spatial radio channels for multiple users while SPE4000 estimates antenna and signal combiner tap weights. Both PROPSim C8 and SPE4000 have extremely high calculation speed that enables real-time operation of adaptive array antennas to be tested. Section 5 presents also results on experiments conducted to demonstrate effectiveness of the PROPSim C8 and SPE4000 joint operation.

2 SYSTEM MODEL

The mathematical model of mobile single propagation channels used in PROPSim C8 is a linear time-varying filter [2] with an impulse response given by

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$$h(t,\tau)=\sum_{k=1}^{L}\beta_k(t)\delta[\tau-\tau_k(t)]e^{j\varphi_k(t)},$$

where t and τ are, respectively, the observation time and the operation time of impulse. L is the number of multipath components, $\beta_k(t)$, $\tau_k(t)$, $\varphi_k(t)$ are the time-varying amplitude, delay, and phase, respectively, and $\delta(*)$ is a delta function.

A complex baseband expression of the N-dimensional vector channel is given by [1]

$$\mathbf{x}(t)=\mathbf{h}(t)+\mathbf{g}(t),$$

where

$$\mathbf{h}(t)=\sum_{k=1}^{L}z_k(t)D(t-\tau_k)\mathbf{a}(\theta_k)+\sum_{j=1}^{I}\sum_{i=1}^{L_j}z_{ij}(t)U_j(t-\tau_{ij})\mathbf{a}(\theta_{ij})$$

is the antenna array output vector in the absence of noise. $\mathbf{g}(t)$ is a band-limited additive Gaussian noise vector. I is the number of interferers. L is the number of propagation paths for the desired user, and L_j is the number of propagation paths for j-th interferer. $D(t)$ and $U_j(t)$ are, respectively, the desired user's and j-th interferer's transmitted baseband signals. $z_k(t)$ ($=\beta_k(t)\exp(j\varphi_k(t))$) and $z_{ij}(t)$ are the fading complex coefficients with the desired k-th path and the j-th interferer's i-th path components, respectively. τ_k and τ_{ij} are the delays of each path. θ_k denotes the Direction of Arrival (DoA) of the desired user's k-th path and θ_{ij} is the DoA of the j-th interferer's i-th path. $\mathbf{a}(\theta_k)$ and $\mathbf{a}(\theta_{ij})$ are the array responses for the DoA's.

Generally speaking, from each transmitter (either desired or interference) to each antenna element, the impulse response should be defined independently, but typically they are highly correlated.

To fully exploit the benefits of the multipath propagation, S/T receivers have to be able to first separate signal components having different delays and different DoA's, and then combine them. S/T receiver has to have taps on the spatial- and temporal-domains to achieve this goal, and they are adaptively adjusted according to the radio channel environment. A reasonable way to determine the tap weights is based on the minimum mean squared error (MMSE) criterion, for which the recursive least square (RLS) algorithm may be used.

Computational complexity with the RLS algorithm is in the square order of the tap number L to be determined. For narrowband systems, digital signal processor (DSP) may handle the computation for the RLS algorithm because the channel's temporal dispersion, normalized by the symbol duration T, is relatively small (L is relatively small). For broadband systems, channel's temporal dispersion becomes quite large (L becomes large), for which it is difficult for DSPs to determines the L taps in real-time. Systolic array implementation of the RLS algorithm is a very reasonable solution to this problem.

3 PROPSIM C8 VECTOR CHANNEL SIMULATOR

Narrowband hardware fading simulators were introduced in the mid 1970's. Feasibility of wideband simulators was discussed in 1990's [6], and state-of-the-art technologies finally have made real-time broadband vector channel simulators commercially available recently [1], [7], [9] and [10].

The PROPSim C8 multichannel simulator can simulate up to eight independent fading channels in real-time. For each of the eight channels phase rotations on the antenna elements associated with the incident paths' DoAs, corresponding to the array response vector, are generated for any type of antenna geometry. Channel models are defined by software. Digital hardware operates at 80 MHz clock rate, and it performs up to 768 parallel multiplications at each clock cycle (12.5 ns), which makes real-time system operation possible. The simulator has RF, Analog Baseband (ABB), and Digital Baseband (DBB) interfaces. The DBB interface enables also non-real-time (off-line) simulations. Table 1 summarizes the hardware specifications of the PROPSim C8 simulator.

Table 1. Hardware Specifications of PROPSim C8

Item	Specification
Number of channels	2, 4, 6 or 8
Simulation interfaces	RF, ABB and DBB
RF center frequency	350 MHz ... 6 GHz
RF bandwidth	70 MHz
Tap spacing	12.5 ns
Maximum delay	400 µs
Maximum Doppler shift	23 kHz

PROPSim C8 is commercially available, and is provided by Elektrobit Ltd., Finland (see Figure 1). More information about PROPSim C8 can be found from PROPSim web site [11].

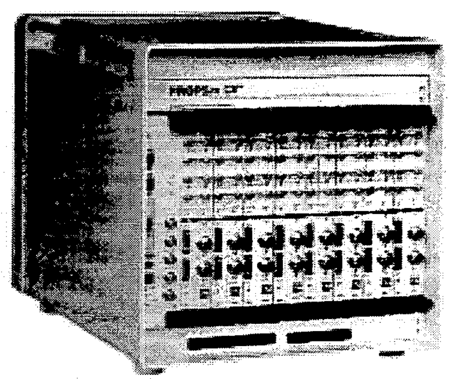

Figure 1. PROPSim C8

Whole hardware is controlled by a system controller, which includes both real-time part and an internal PC. The controller sends channel model data to the baseband units of the simulator, and controls both baseband and RF units.

Graphical User Interface (GUI) with channel modeling and simulator control software operates under the Windows 2000 operating system. Channel models can be either created by software or imported from other software such as Ray-Tracing software and/or MatLab. Importing field measured data obtained as results of channel sounding measurement campaign is also possible. Channel modeling software uses well-approved channel modeling methods based on Refs. [3], [5] and [8]. Channel modeling software covers both stochastic and semi-deterministic modeling methods. For stochastic channel modeling, geometric constellation (DoA and antenna array coordinates) data or spatial correlation matrix have to be input [9]. PROPSim C8 can also simulate measured channels, which is implemented as a playback mode.

PROPSim C8 can support different network topologies including antenna array test without and with interference (Figure 2 and Figure 3, respectively). These different network elements (transmitters and receivers) are connected to PROPSim C8 hardware and can be controlled via the GUI.

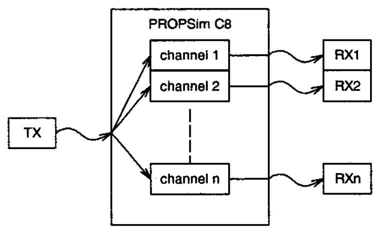

Figure 2. Antenna Array Test without Interference

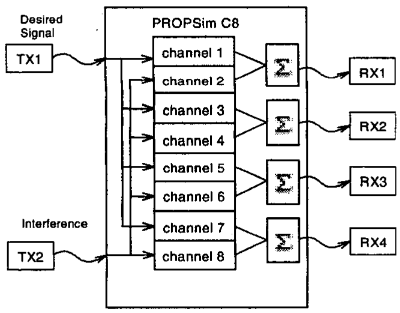

Figure 3. Antenna Array Test with Interference

3.1 Phase and Amplitude Calibration

Phase and amplitude errors among the multiple channels are critical factors in terms of the accuracy when simulating adaptive array antennas, and thus they should be calibrated periodically. The basic idea for the system calibration is to tune the simulator's up- and down-converters channel-by-channel with reference to a certain channel (The first channel may be used as a reference without the loss of generality) at a fixed RF setup. Phase and amplitude of each channel can be adjusted via the GUI. Phase and amplitude responses of the channels are compared and verified by using a network analyzer.

3.2 Splitting and Combining RF Band

Bandwidth of the system is limited by Analog-to-Digital (A/D) and Digital-to-Analog (D/A) converter's speed as well as by digital circuitry's operation speed. PROPSim C8 uses 80 MHz clock rate (both I- and Q-Channels), which corresponds to RF bandwidth of up to 70 MHz. The signal bandwidth can further be increased by a parallel operation of the multiple channels [7].

Broadband signal can be split into two or more RF segments. Signal is down-converted with different local oscillator signals (RFLO's), by which different frequency bands are down-converted into different baseband segments. This parallel operation increases the system bandwidth X times as large as without parallel operation, where X is the number of parallel channels (see Figure 4).

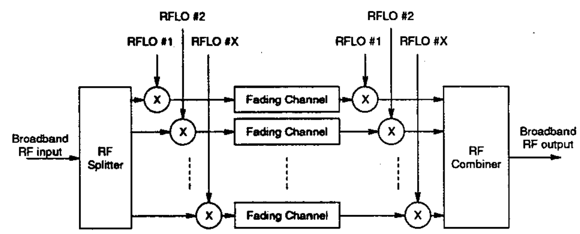

Figure 4. Splitting RF band

This solution offers the capabilities of testing and simulating very broadband systems. Fading channels can also be different, which provides more degrees of freedom in channel modeling. However, the splitting of signals in the RF band may cause some distortion and/or incoherence especially in the corners of each sub-band. They can be compensated by proper FIR and/or IIR filtering in the complex baseband domain. The drawbacks of the compensation are the required hardware and slightly decreased bandwidth. Practically 100 MHz bandwidth is achievable with two PROPSim C8 parallel channels.

4 APPLICATION TO S/T-EQUALIZER

As widely understood, S/T equalizer techniques are advantageous in making effective use of multipath propagation in broadband systems. The PROPSim C8's capabilities well suits S/T equalizer simulations and measurements. With combination of PROPSim C8 and a parameter estimator, tap weights in S/T equalizer can be estimated in real-time, thereby on-site testing of S/T equalizer systems is made possible. Figure 5 shows an example of S/T equalizer test system, where the S/T equalizer has both spatial and temporal taps to cancel interference components and to combine desired delayed path components.

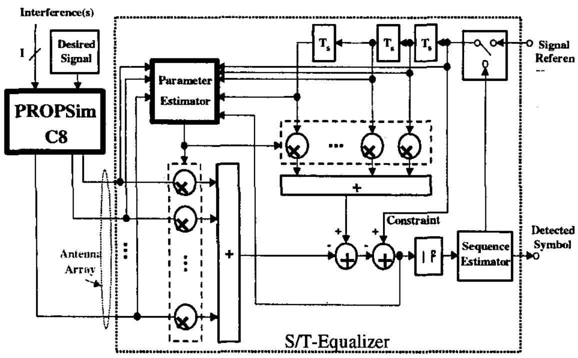

Figure 5. Application to S/T Equalizer

5 SIMULATIONS AND MEASUREMENTS

5.1 Parallel Channel Operation

Increased simulator bandwidth achieved by parallel channels was proven through experiments, where two channels were operated in parallel. To confirm the effectiveness of the method, system performance was optimized with digital filters. Figure 6 and Figure 7 show measured amplitude and group delay characteristics, respectively.

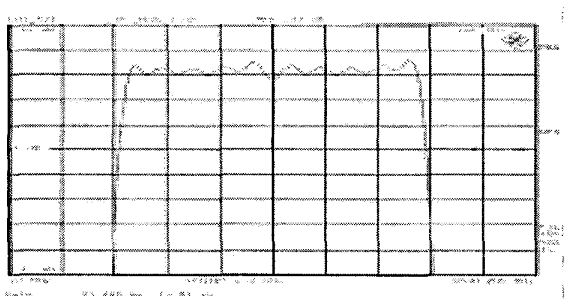

Figure 6. Amplitude response of broadband channel

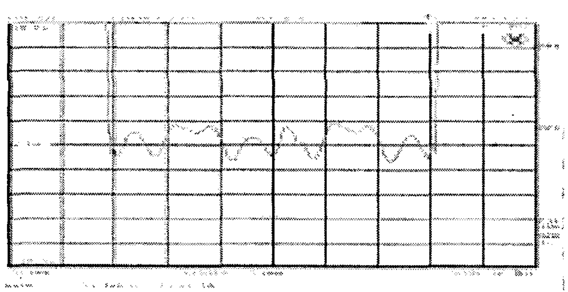

Figure 7. Group delay response of broadband channel

In this experiment, measured amplitude variation is less than 2 dB peak-to-peak and group delay variation is less than 5 ns peak-to-peak within 100 MHz band.

5.2 Real-Time Adaptive Array Antenna Simulation

A real-time adaptive array antenna simulation was conducted using PROPSim C8 and an RLS parameter estimator, where, for simplicity, frequency-flat fading was assumed. SPE4000, a systolic array implementation of the recursive least square (RLS) algorithm, was used as the parameter estimator in the simulation [1] and [4]. The systolic array implementation makes it possible to determine the adaptive array antenna weights drastically faster than with DSP-based implementations: SPE4000 can estimate 10 complex parameters within 35 micro- seconds. Figure 8 shows a block diagram indicating that how the systolic array parameter estimator can be used in adaptive array experiments.

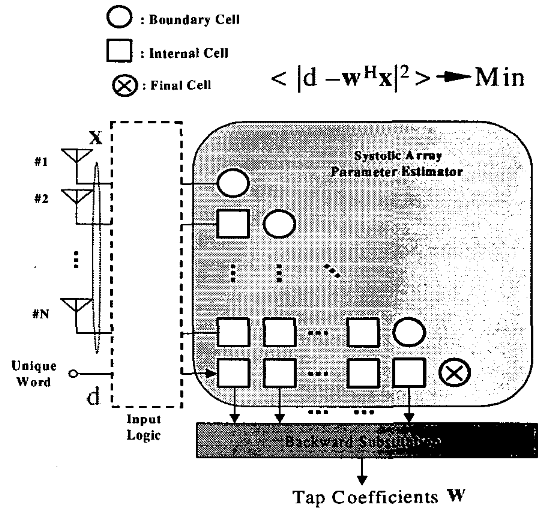

Figure 8. Parameter Estimator

SPE4000 can be used not only in adaptive array antennas but also for S/T equalizers as well as multiple-input multiple-output (MIMO) systems so far as the parameters are determined based on the Minimum Mean Square Error (MMSE) criterion. SPE4000 is implemented using a Very Large Scale Integration (VLSI) technology, and its commercial version is provided by Cybernetics, Japan. Figure 9 shows the mechanical outlook of SPE4000.

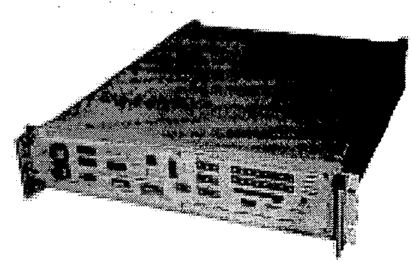

Figure 9. SPE4000

The SPE4000 was used in the simulation. A block diagram of the simulation configuration is shown in Figure 10. In the simulation, a four paths scenario was assumed: two paths for desired signals with DoA's of 30° and 150°, and the other two paths for interference signals with DoA's of 190° and 230°. A four-element circular array antenna was assumed. Figure 11 shows beam patterns obtained as results of simulations with per-element received signal-to-noise power ratio (SNR) as a parameter. It can be seen that, as indicated in the theories [2], the deeper the nulls formed, the larger the SNR value.

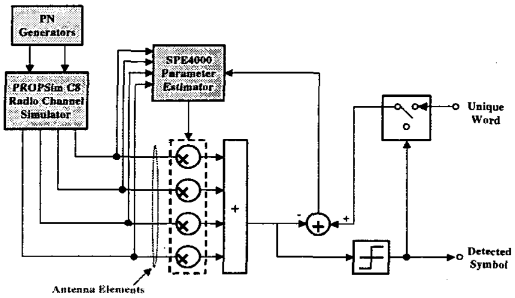

Figure 10. Simulation Configuration

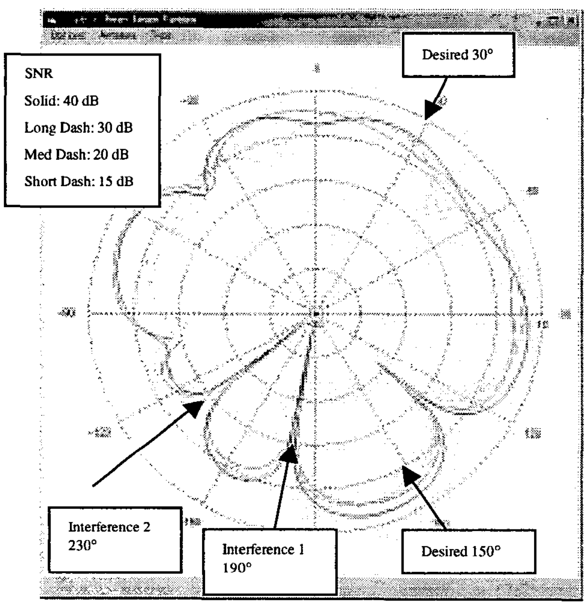

Figure 11. Beam Pattern Figure

5.3 Joint Operation

A real-time adaptive array antenna simulation is taking place in parallel to the conference nearby to demonstrate the effectiveness of the joint operation of PROPSim C8 and SPE4000, where, for example, beam pattern is shown via computer display.

6 CONCLUSION

In this paper, PROPSim C8 broadband vector channel simulator was introduced. Methods for increasing simulator bandwidth and calibrating multiple RF channels were discussed. A test platform of S/T equalizer including PROPSim C8 and SPE4000 parameter estimator was introduced. The platform can be used for algorithm research, system design, testing/debugging, and standardization.

7 ACKNOWLEDGMENTS

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