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N85-16953

MODELING TECHNIQUES USED IN THE COMMUNICATIONS LINK ANALYSIS AND SIMULATION SYSTEM (CLASS)†

Walter R. Braun*
Teresa M. McKenzie

LinCom Corporation
P.O. Box 15897
Los Angeles, CA 90015-0897
(213) 381-3701

ABSTRACT

CLASS (Communications Link Analysis and Simulation System) is a software package developed for NASA to predict the communication and tracking performance of the Tracking and Data Relay Satellite System (TDRSS) services. This paper describes some of the modeling techniques used in CLASS.

1. INTRODUCTION

The Communications Link Analysis and Simulation System (CLASS) presently under development for NASA/Goddard Space Flight Center (GSFC) is an integrated set of FORTRAN programs capable of predicting the compatibility and performance of the communication and tracking links for all services and signal formats supported by the Tracking and Data Relay Satellite System (TDRSS). CLASS contains detailed models for the TDRSS spacecraft and ground terminal hardware, including Shuttle-unique equipment, and models for the effects of the transmission medium (rain attenuation, multipath, radio frequency interference (RFI). CLASS allows the modeling of the transponder of a TDRSS user such as Shuttle either based on a specific hardware implementation or based on a set of parameters describing the signal characteristics at the RF interface between TDRSS and the user transponder. These parameters are used by NASA/GSFC to specify the quality of the user's signal at this interface and are, therefore, referred to as user constraints [1].

CLASS is capable of verifying the compatibility of a particular transponder design with the TDRSS signal formats and predicting the system performance in terms of all the performance parameters of interest to the user. These include data integrity (bit error probability, bit slippage probability, probability of carrier phase slips in MPSK systems), synchronization (tracking jitter, slip rates, loss of lock probability), tracking (range and range rate), and acquisition (acquisition time, probability of false lock) performance.

The capabilities and structure of CLASS are presented in more detail in another paper in these Proceedings, "Communications Link Analysis and Simulation System" by Robert Godfrey. The effort made to validate CLASS is described in another paper in the Proceedings, "Validation of the Communications Link Analysis and Simulation System (CLASS)" by the same authors as the current paper.

The purpose of this paper is to describe some of the modeling techniques used in CLASS. The components of TDRSS and the performance parameters to be computed by CLASS are too diverse to permit the use of a single technique to evaluate all performance measures. Hence, each CLASS module applies the modeling approach best suited for a particular subsystem and/or performance parameter in terms of model accuracy and computational speed. It was one of the challenges of the CLASS development to design a software structure which allows these diverse modules to share one system database.

The following sections provide a brief description of the modeling techniques used for four major parts of CLASS: the bit error rate performance computation (Section 2), the synchronization/tracking subsystem (Section 3), the acquisition subsystem (Section 4), and the evaluation of RFI effects (Section 5).

2. COMPUTATION OF BIT ERROR RATE

The channel model for the bit error rate analysis must account for the signal distortion occurring in the transmitter, the relay satellite, as well as the receiver. A typical return link channel model is shown in Figure 1. The complexity of this channel model, particularly the mixing of linear and nonlinear elements, prevents the use of strictly analytical performance evaluation techniques. Similarly, the low bit error probabilities of interest (the design BER is 10^{-5}) make Monte Carlo type simulations prohibitively slow. The approach used in CLASS combines elements of both techniques. The signal is represented as a sampled waveform which allows the modeling of all user constraints. Linear

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[†] This work was supported by NASA Goddard Space Flight Center under contracts NAS 5-27240, NAS4-25681, NAS5-23591.

[*] W. Braun is currently with Brown, Boveri & Co., Limited, Baden, Switzerland.

signal distortions are easily incorporated through a fast Fourier transformation (FFT) of the waveform and appropriate processing in the frequency domain. The interaction between the signal, adjacent channel waveforms, and thermal noise in nonlinear elements (power amplifiers, limiters) is modeled through a modified Barrett-Lampard expansion developed for this program and described elsewhere [2].

The receiver model operates on the sampled signal and a statistical representation of the thermal noise and interference. First, the effect of the signal characteristics on the synchronization systems (PN code, carrier, clock recovery) is computed. The effect of these subsystems on the recovered symbols is then included in the bit error performance evaluation by computing first the BER conditioned on the various synchronization errors and then averaging over the appropriate probability densities. The BER in the case of coding and 8-level quantization at decoder input is computed via the R_0 approximation [3]. The channel cut-off rate R_0, computed from the channel output probabilities conditioned on channel input, is assumed to fully characterize the channel. The BER is assumed to be a function of code rate and R_0 only, those functions being given in [4].

The above approach is not intended as a universal modeling tool for nonlinear channels. The modified Barrett-Lampard expansion describes the spectral characteristics of the output of the nonlinearity and it requires an excessive number of terms when highly nonlinear elements, such as hard limiters, are included in the channel model. Similarly, the approximations made in the statistical representation of the noise and interference become inaccurate when highly nonlinear elements are modeled. However, for the characteristics of the TDRSS channels the accuracy of the models was verified by analysis and comparison to Monte Carlo simulations.

To point out the importance of a comprehensive link model, the single parameter sensitivities with a perfect signal and a linear, wideband channel are compared in Figure 2 with sensitivity results obtained with a typical TDRSS link model. The plots show that single parameter sensitivity results with a perfect signal and a linear, wideband channel can be quite misleading. Similarly, Table 1 shows that for another typical link the sum of the degradations that result from increasing each of several parameter values separately can be different from the degradation that results from increasing all the values at once.

3. MODELING OF THE SYNCHRONIZATION/TRACKING OPERATION

The synchronization subsystems modeled are the PN code, carrier, and clock recovery loops in their various implementations in the TDRSS ground station. Several performance parameters are of interest:

(1) the tracking jitter due to thermal noise and signal amplitude and phase variations,
(2) the tracking offset due to loop stress and vehicle dynamics (Doppler, acceleration),
(3) the rate of cycle slips due to all the above sources and to untracked clock jitter,
(4) the probability of dropping lock due to vehicle and antenna dynamics and signal dropouts.

These subsystems are modeled by a combination of analysis and simulation. The analysis accounts for the effect of thermal noise, phase noise (clock jitter), and vehicle and antenna dynamics on the synchronization performance (based on nonlinear tracking models [5]), while the signal waveform generated for the BER performance evaluation is used to characterize the effect of waveform distortions. The phase-tracking jitter generated by these signal distortions is generally referred to as pattern jitter. By linearly combining it with the thermal noise effect the overall subsystem performance is obtained.

The characterization of the tracking performance requires, in addition to the above aspects, an accurate model of the low-frequency phase noise in the TDRSS and user transponder. All TDRSS links can operate in a coherent turnaround mode. This means that the phase noise processes on the ground, in the TDRS, and in the user equipment are correlated. However, due to the small phase error values of interest, linear models apply and the system can be characterized by a linear network. A thorough description is provided in [6].

4. MODELING OF SIGNAL ACQUISITION

The signal acquisition process includes the search for the PN code epoch (for spread spectrum signals), the carrier frequency and phase acquisition, and the clock synchronization. In addition, the Ku-band links require the spatial acquisition of the autotrack system.

Analytical models were developed for the different hardware implementations used in the TDRSS ground station and various user transponders. The signal model used reflects the user constraints as well as the linear and nonlinear distortion effects of the channel.

The PN acquisition model computes the characteristic function of the search time based on the a priori code epoch uncertainty and the search algorithm. Specific cases of interest include single dwell time, dual dwell time, and variable dwell time systems for a circular search over the whole code or an expanding window search over a small part of the long code (e.g. during reacquisition). A detailed description of the analytical approach is given in [7,8].

The carrier acquisition algorithms modeled include frequency-locked loop (FLL) aiding, swept acquisition, and frequency pull-in (self acquisition). The modeling is based on analytical models [5,9,10] with appropriate modifications to account for signal distortions (user constraints and channel effects). The FLL may operate with a low SNR at the input to the frequency discriminator. The model includes, therefore, a spike noise component at the discriminator output. The FLL bandwidth is small, however, which permits the use of a linearized loop model.

A major component of these models is the acquisition/tracking monitor and the transition between the two modes. The response time of the monitor can contribute significantly to the overall acquisition time. Also, the implementation of this monitor determines the probability of false lock.

The clock recovery loops modeled are all self-synchronizing. With typical clock stabilities, these systems do not contribute significantly to the acquisition time.

5. MODELING OF RFI EFFECTS

It is expected that some of the TDRSS links will be subject to high-powered RFI. This interference may be a mixture of pulsed CW signals and noise pulses of a few microseconds duration with random arrival times.

CLASS is designed to account for the RFI effect on all aspects of TDRSS performance. First we discuss modeling of the effect on BER, then on synchronization and acquisition, and last on tracking.

Two approaches were taken in the case of BER. First an analytical model was developed based on assumptions that hold for the general TDRSS S-band user. The model breaks down for the Shuttle S-band return link in the prediction of decoder performance. For this reason, a second approach, a Monte Carlo type simulation, was also taken. A benefit of having both approaches is that they serve to verify each other.

The analytical approach in the case of BER is based on the sample-sum approximation to the matched-filter output [11]. The approach is implemented in different ways depending on whether the symbol rate is high or low relative to the inverse of the RFI pulse duration. In both cases the characteristic function of the matched-filter output is obtained. From it, in the case of a convolutionally encoded link, the cut-off rate R_0 is computed, from which in turn BER is computed. An early account of the modeling approach is given in [12]. However, extensive testing demonstrated the need for a host of refinements to insure good accuracy for all RFI environments and data rates. These updated models are described below.

In the high-rate analytical model for BER at most one RFI pulse is assumed to occur in a symbol duration. The Gaussian or non-Gaussian characteristic function of the matched-filter output is obtained, conditioned on no RFI or on the type and power of RFI occurring in the symbol. For CW RFI conditioning is also on the RFI frequency and initial phase. The conditional characteristic functions are weighted and summed to yield the unconditional function. Since interleavers are used by the general TDRSS S-band user (but not Shuttle) for high symbol rates, it can be assumed for the decoder model in that case that the channel is memoryless.

In the low-rate analytical model for BER, each RFI pulse is assumed to be wholly contained in one symbol. The characteristic function of the contribution to the matched-filter output of one RFI pulse is computed, conditioned as above. This characteristic function is normalized by the characteristic function of no RFI occurring for the pulse duration. The average of all such functions is obtained. Poisson pulse arrival statistics are employed to form the non-Gaussian characteristic function of the matched-filter output as the product of a term involving the function just described and the no-RFI characteristic function.

In the Monte Carlo type simulation to model the RFI effect on BER, no interleaver or deinterleaver is present, which reflects the case of the Shuttle return links.

The models of the RFI effect on all the synchronization subsystems and most of the acquisition subsystems are similar. In these subsystems there are a filter with bandwidth roughly equal to the symbol rate, a nonlinear element and possibly some other elements, and then a filter with a bandwidth less than the lowest symbol rate. As in the BER model, two analytical models are actually used. For low symbol rates the first filter is assumed to average the RFI conditions. For high symbol rates the first filter is assumed wide enough to pass the RFI undistorted and the second filter is assumed narrow enough to do the averaging. The results are insensitive to the exact symbol rate that is chosen for the cross-over point between the models. For swept carrier acquisition the time during which the loop can pull in is assumed long enough to contain many pulses of each type of RFI.

The RFI affects Doppler tracking by increasing carrier phase jitter and cycle slips.

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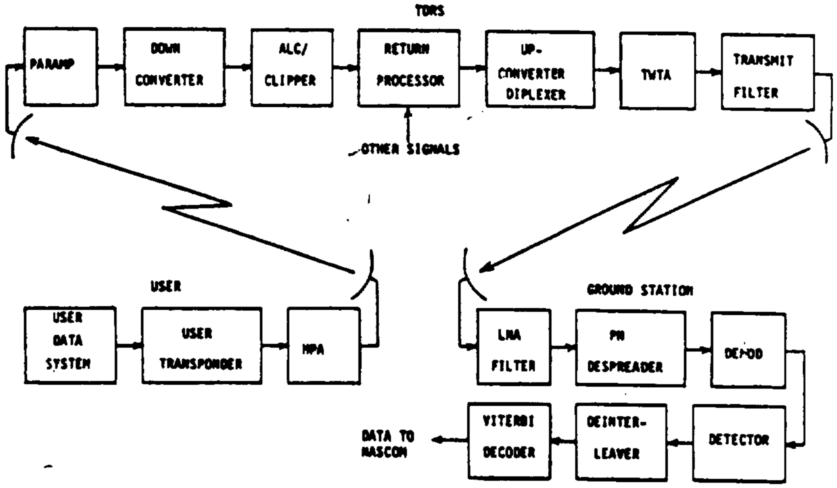

Figure 1. TYPICAL LINK MODEL.

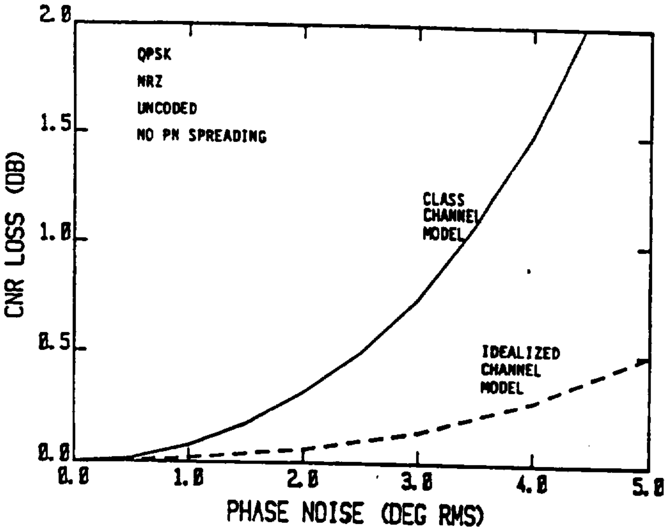

Figure 2a. COMPARISON OF PARAMETER SENSITIVITIES FOR CLASS CHANNEL MODEL AND IDEALIZED CHANNEL MODEL FOR UNTRACKED PHASE NOISE.

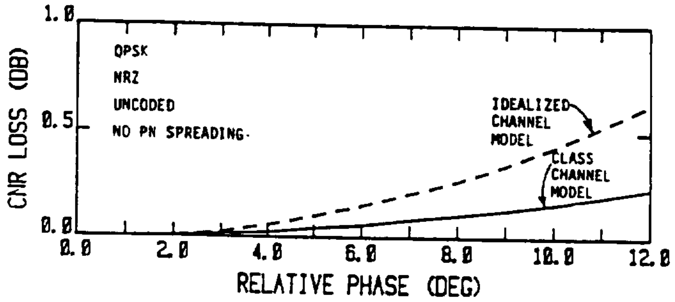

Figure 2b. COMPARISON OF PARAMETER SENSITIVITIES FOR CLASS CHANNEL MODEL AND IDEALIZED CHANNEL MODEL FOR MODULATOR PHASE ERROR.

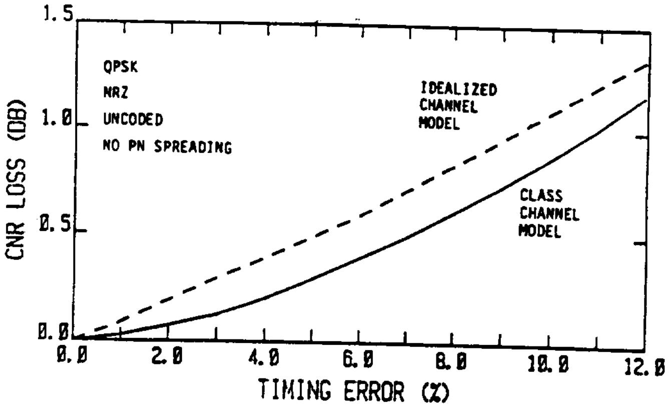

Figure 2c. COMPARISON OF PARAMETER SENSITIVITIES FOR CLASS CHANNEL MODEL AND IDEALIZED CHANNEL MODEL FOR RECOVERED CLOCK PHASE ERROR.

Table 1. CNR LOSS DUE TO SEVERAL PARAMETERS EXCEEDING NOMINAL VALUES (COURTESY OF ROBERT GODFREY OF NASA).

	Parameter	Nominal Value	Actual Value	CNR Loss
1.	Modulator Phase Imbalance	3°	7°	0.2 dB
2.	Modulator Gain Imbalance	±0.25 dB	±0.8 dB	0.87
3.	Phase Nonlinearity	±3°	±9°	0.5
4.	Gain Flatness	±0.3 dB	±3 dB	--
5.	Gain Slope	±0.1 dB/MHz	1	0.15
6.	AM/PM	12°/dB	20°/dB	0.58
7.	Phase Noise	1°	3°	0.1
	Composite Impact			3.18 dB

(BPSK, NRZ, Rate-1/2 Coding, No PN Spreading)