SCCC Turbo Equalizer/Decoder for X-band Nano Satellite High-Speed Downlink System

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To provide data rate more than 100 Mbps for nano satellite communications, we have developed an X-band downlink system with a modulation symbol rate of 100 Msps. The received signals of nano satellites tend to suffer much more distortion due to the transmitter and channel constraints. Several effective techniques based on turbo equalizer/decoder have been developed and verified via computer simulation therefore, the obtained results apply to the downlink system design.

Key Words: GaN Power Amplifier, Nano Satellite Communication System, Predistortion, Turbo Code, Turbo Equalizer

1. Introduction

Nano satellite technologies have been recognized as potential candidates for new satellite applications. Japan's nano satellite center (NSC) is developing advanced nano satellite technology to realize new industrial space systems and services.¹⁾ Several nano satellites with a mass of less than 50 kg have been developed and launched in recent years.²⁾ Different applications, as well as scientific missions, have been proposed for future satellite industry.³⁾ A high-speed downlink system specialized to nano satellites is consequently required to achieve the various missions. However, since conventional high-speed downlink systems have been designed for large satellites, constraints of transmitter for nano satellites are more severe than those for large satellites due to low-power, light-weight, and low-cost modules. Thus, high-speed downlink system dedicated to nano satellites must be developed for future satellite applications.

Consultative Committee for Space Data Systems (CCSDS) 131.2-B-1 recommendation⁴⁾ was published to support a wide range of spectral efficiency values and data rates for high-data-rate telemetry applications in March 2012. Comprehensive coding and modulation schemes are defined as adaptive coding and modulation (ACM) formats including serially concatenated convolutional turbo coding (SCCC) with various data rates using punctured code and m -ary modulation, where the modulation order m is set to 2, 3, 4, 5, and 6. The system design and evaluation can be found in the literature.⁵⁻⁸⁾ The downlink systems employing CCSDS 131.2-B-1 for large satellites with data rate more than 1 Gbps and occupied bandwidth up to 500 MHz have been reported.^{5, 6)}

The characteristics of a satellite channel are nonlinear and dispersive due to both amplitude and phase distortion. Moreover, a high-speed satellite communication system is likely to perform worse owing to channel- or circuit-induced factors. In addition, the weak received signal must be handled

by ground receiver due to the constraint transmit power.

To achieve high-speed transmission and overcome the above difficulties, we have developed an X-band downlink system for nano satellites employing the CCSDS 131.2-B-1 signaling formats of $m = 2$ and 4 with a modulation symbol rate of 100 Msps. At the receiver, SCCC turbo decoder combined with a soft interference canceller (SIC) turbo equalizer and distortion compensation techniques has been developed to obtain the maximum possible coding gain for each ACM format.⁹⁾ At the transmitter, a look-up table (LUT) based digital predistorter (DPD) for memoryless nonlinear channels has been designed to mitigate nonlinearity of power amplifier (PA) and IQ-imbalance of quadrature modulator.¹⁰⁾ The linear/nonlinear distortion sources based on experimental measurements were modeled, and then the downlink system performances were evaluated via simulation using a signal processing worksystem (SPW).¹¹⁾ The results indicate that the highest data rate of 320 Mbps is achieved in the nano satellite downlink channel.^{9, 10)}

Since several newly developed modules on the transmitter engineering model (EM) have been implemented, the more accurate degradation factors can be modeled based on the measurements. Specifically, a 2 W GaN-based high PA (HPA) of class AB with high power efficiency has been developed for the nano satellite transmitter, and then a practical PA model with respect to the actual transmitting waveform has been designed. The system simulation combined with the modified PA model is expected to obtain a more accurate performance than previous works.

This paper is organized as follows. The nano satellite high-speed downlink system structure is summarized in Section 2. The practical PA modeling is described in Section 3. The system performance analyses via computer simulation are discussed in Section 4. Finally, conclusions are given and future work is outlined in Section 5.

Fig. 1. Physical layer frame structure of CCSDS 131.2 B-1.

Fig. 2. System block diagram.

Fig. 3. Block diagram of SCCC turbo equalizer/decoder.

2. Downlink System Structure

2.1. Signaling format

In CCSDS 131.2-B-1 recommendation, a physical layer (PL) frame consists of a PL header, followed by 16 codeword sections (CWSs), as shown in Fig. 1. The PL header is composed of a frame maker (FM) of 256 known symbols for the initial acquisition, and a frame descriptor (FD) of 64 encoded symbols with mapping 16 information bits of the ACS format number to a 64 bit code word. Since each CWS consists of 8100 modulation symbols regardless of the selected ACM format, common modules can be implemented after the frame generator because the output modulation symbols have a fixed symbol rate. After calculating link budget for the planned nano satellite downlink, the ACM formats 1 to 6 and 13 to 17 were selected to transmit over the nano satellite channel. In other words, the possible modulation schemes to meet the requirement of link budget are modulation order $m = 2$ and 4. The relationship between the number of information bits and coding rates per CWS is listed in Table 1. Note that 16-QAM is adopted instead of 16-APSK for $m = 4$ since the minimum Euclidean distance between constellation points of the former is larger than that of the

Table 1. ACM formats of high-speed downlink system.

QPSK			16-QAM		
ACM	Info. bits	Rate	ACM	Info. bits	Rate
1	5758	0.355	13	19198	0.593
2	6958	0.430	14	21358	0.659
3	8398	0.518	15	23518	0.726
4	9838	0.607	16	25918	0.800
5	11278	0.696	17	28286	0.874
6	13198	0.815	8100 mod. symbols per CWS		

Table 2. System specification.

RF center frequency	8160 MHz
Earth viewing altitude	600 km
Transmit power	2 W
SRRC filter	$\alpha = 0.5$, 32 taps
Modulation symbol rate	100 Msps
Oversampling frequency	400 MHz
SCCC encoder	Generator polynomials (octal): 7, 5, $r = 1/2$, 4-state RSC code
MAP-Decoder	BCJR algorithm Number of iterations = 16
Equalizer	$P(f)$: LF = 13 taps, fractional 1/2 $Q(f)$: LB = 7 taps, fractional 1 Number of iterations = 3
Adaptive algorithm	LMS ($\mu = 0.015/0.005$)

Fig. 4. Block diagram of PSB model.

latter and the effective compensation techniques against linear/nonlinear distortion have been developed. However, 16-APSK modulation is also implemented in the experimental system to send messages according to the signaling format of CCSDS 131.2-B-1 recommendation. Thus, we can compare the performance of the 16-APSK system with that of the 16-QAM system in the nano satellite channel.

2.2. System structure

A block diagram of the equivalent lowpass model¹²⁾ for the nano satellite high-speed downlink system is shown in Fig. 2. These blocks except the power amplifier have the same features as the previous work.^{9, 10)} The system specifications used in evaluations are listed in Table 2.

On the transmitter side, a CCSDS 131.2-B-1 format generator outputs modulation symbols that consist of in-phase and quadrature (IQ) components, depending on the selected ACM format, and then the modulation symbols are passed to a square-root raised cosine (SRRRC) filter followed by DPD, quadrature modulator, and PA.

The DPD is illustrated in the upper left of Fig. 2. The complex signals obtained by the inverse AM/AM and AM/PM characteristics of the PA with regard to temperature variations are stored in LUT. The optimum LUT is adaptively updated based on periodically measured monitor signals from quadrature modulator and PA. Then the optimum gain and phase from the LUT are multiplied by input signals. These predistorted signals are multiplied by an inverse matrix $\hat{\mathbf{A}}^{-1}$ relative to estimated IQ-imbalance value.

On the receiver side, four times oversampled complex baseband signals are sent to the receiver, as shown in Fig. 2. The input signals are first processed by a signal searcher to obtain the PL header timing by correlating the received signals with the known FM symbol sequence. After finding the timing corresponding to the maximum correlation value, the initial parameters, such as frequency deviation, phase offset, and tap weights of SIC equalizer, are estimated, and then passed to frequency tracking loop (FTL), time tracking loop (TTL), and SIC equalizer, respectively. The FTL removes the residual Doppler frequency and carrier phase offset from the input signals based on the Costas loop.¹²⁾ On the other hand, the TTL provides the optimum symbol timing based on the Gardner loop,¹²⁾ and sends the suitable symbols (i. e. the samples equal to twice the modulation symbol rate) to the

SCCC turbo equalizer/decoder. As shown in Fig. 3, the SCCC turbo equalizer/decoder consists of two feedback loops according to turbo principle.¹³⁾ Specifically, the upper feedback loop, SIC turbo equalizer, adaptively compensates linear/nonlinear distortion and multipath interference when updating tap weights of forward and backward FIR filters to minimize the errors between the received symbol and iteratively regenerated symbol. The lower loop, SCCC turbo decoder, decodes the equalized symbol sequences in an iterative fashion, with the two soft-in soft-out (SISO) decoders alternatively updating their probability measures. After a given number of iterations, the outer SISO decoder outputs the hard-decision bit sequence $\hat{a}_i$. More details of the SCCC turbo equalizer/decoder can be found in our previous work.⁹⁾

3. PA Modeling

3.1. PSB model

Different PA modeling techniques have been proposed in the literature.^{11, 14, 15)} There are two main categories of PA models: analytical model and empirically based model. Since we have obtained measurements of the different HPAs and want to evaluate system performances using the equivalent lowpass model with reasonable complexity, the empirical model, called Poza-Sarkozy-Berger (PSB) model¹²⁾, has been adopted as the PA model. The PSB model consists of two branches as shown in Fig. 4. The upper branch, including a LUT and pre- and post-filters, is configured to model an AM/AM path and output distorted gain $g_{AM}(t)$. The measured AM/AM characteristic at the center frequency is stored in the LUT to generate memoryless distortion. The pre- and post-filters yield frequency dependence corresponding to finite impulse response (FIR) filter whose tap weights are obtained by finding horizontal and vertical shift values from the AM/AM curve of the reference center frequency. Similarly, the lower branch is configured to model AM/PM path and output distorted phase $\theta_{PM}(t)$. Finally, the obtained gain and phase are transformed into complex signals with memory effect corresponding to the FIR filters.

3.2. Two stage PSB model

Recently, GaN high electron mobility transistors (HEMTs) are promising PA devices to improve power added efficiency (PAE) for wireless communications. Then, we develop GaN

Fig. 5. Performances of GaN HPA at reference frequency.

Fig. 7. Performances of driver amplifier at reference frequency.

(a) AM/AM portion

(a) AM/AM portion

(b) AM/PM portion

(b) AM/PM portion

Fig. 6. Horizontal and vertical shift differences of GaN HPA.

Fig. 8. Horizontal and vertical shift differences of driver amplifier.

HPA of class AB with the bandwidth of 200 MHz in X-band. The GaN HPA achieves more than 40 percent PAE.

The HPA performances required for PSB model were measured as shown in Figs. 5 and 6. In Fig. 5, the AM/AM curve is almost linear below the input power of 24.65 dBm, whereas the output power gradually saturates with input power and has no saturation level within the practical input power range. The AM/PM curve varies within several degrees below the input power of 24.65 dBm. The curves corresponding to the frequency dependence are plotted in Figs. 6 (a) and (b), respectively. The proper values of horizontal and vertical displacements are found using MMSE estimation given by the shift values between the characteristic curves of the reference frequency and all other frequencies. Since target symbol rate is 100 Msps in X-band, the frequency responses that occupy a bandwidth of 200 MHz centered on the

Fig. 9. Block diagram of PA module.

reference frequency with 25 MHz steps are measured for the PSB modeling. The total number of frequency points in each curve is 9. In Fig. 6 (a), horizontal and vertical shift values corresponding to input and output powers of the AM/AM curve are within 2 dB. In Fig. 6 (b), the horizontal shift value of AM/PM ranges about 5 dB and the vertical shift value indicating phase differences ranges about 3 degree.

The PA module implemented in the transmitter EM is constructed from two amplifiers - a driver amplifier followed

Fig. 10. Scatter plots for 16-QAM received signal distorted by a combination of two stage PSB model with or without DPD.

Fig. 11. Scatter plots for 16-QAM received signal distorted by a combination of memoryless PA model with or without DPD.

by the GaN HPA. To obtain the modeling output waveform closer to the EM output, we design a two-stage PSB model using the two types of amplifier measurements, as shown in Figs. 5 - 8. The AM/AM and AM/PM curves of the driver amplifier indicate that the output signal will suffer much less from nonlinear distortion when setting the operating point below the input power of 5 dBm, as shown in Fig. 7.

We present below the procedure of designing the two-stage PSB model with respect to the block diagram of PA module implementing on the transmitter EM, as shown in Fig. 9. As indicated by the vertical dotted line in Fig. 7, the operating point of input power of the driver amplifier is set to 4.55 dBm to avoid the nonlinear region, and then the output power of 24.65 dBm is obtained. This power is assigned to the input power of the GaN HPA, as indicated by the vertical dotted line in Fig. 5. Thus, the output power of 35 dBm corresponding to the input power of 24.65 dBm is obtained. Since the actual output power of the transmitter EM includes the power loss of circuits and cables, the system loss is assumed to be 2 dB for the simulation model. Hence, the actual output power from transmit antenna is assumed to be our target transmit power of 2 W (33 dBm). Note that the operating point is defined as the average power of the input signal to each amplifier.

3.3. Comparison of scatter plots

The effects of distortion caused by different PA models at the sampling instant are readily seen in scatter plots for

Fig. 12. Required E_b/N_0 for $\text{BER} = 10^{-6}$ on two stage PSB model with or without DPD.

received 16-QAM signals. The scatter plots with or without DPD for the two-stage PSB model are illustrated in Fig. 10. For comparison, the scatter plots for memoryless two-stage PA model are also illustrated in Fig. 11. The memoryless models utilize only the two LUTs as shown in Figs. 5 and 7. The effects of two-stage PA model can be seen in comparison with the scatter plots of Figs. 10 (a) and 11 (a). As expected, each constellation point of the two-stage PSB model indicates larger distribution than that of the memoryless model. In other words, the PA model with memory effect causes severe intersymbol interference (ISI). Comparing with or without DPD for the two-stage PSB model as shown in Figs. 10 (a) and (b), the dispersion of each of the predistorted constellation points is smaller than that of non-predistortion. The shape of the predistorted constellation is improved around vertexes and closes to the original square constellation points. However, since the DPD is a memoryless compensation technique, the ISI due to memory effect can not be sufficiently reduced. The residual ISI must be eliminated by using the SCCC turbo equalizer/decoder at the receiver.

4. Performance Evaluation of Downlink System

In our model we have considered that the received signals are affected by PA nonlinear distortion, IQ imbalance, frequency shift, phase noise and WGN, as shown in Fig. 2. We assume that the parameters are set to IQ imbalance of 5 degree, frequency shift of 1 kHz, and the phase noise mask corresponding to X-band signal.⁸⁾ To evaluate the downlink system performances, the values of E_b/N_0 required to achieve a BER of 10^{-6} for all ACM formats with or without the DPD are simulated, as shown in Fig. 12. The curves corresponding to perfect synchronization are also shown as dotted lines. Note that the horizontal axis represents coding rate of each ACM format, as listed in Table 1. In Fig. 12, it is shown that the curves of required E_b/N_0 for QPSK modulation in both "with DPD" and "without DPD" cases are the same. On the other hand, for 16-QAM modulation, the required E_b/N_0 curves in

the case with DPD become less steep, leading to more of E_b/N_0 difference as the coding rate increases. Since ACM formats of 16-QAM with higher coding rate are more susceptible to channel impairments due to tradeoff between coding rate and coding gain, the residual ISI and phase variation seriously degrades BER performance, especially without the DPD.

The link budget for nano satellite downlink was found by setting transmit power of 2 W. The obtained target E_b/N_0 is 7 dB for QPSK and 10 dB for 16-QAM. The simulation results imply that all ACM formats of QPSK modulation with or without DPD are acceptable for the target E_b/N_0 ; the required coding rates of ACM formats of 16-QAM modulation with or without DPD are 0.80 and 0.726, respectively. Assuming modulation symbol rate of 100 Msps in the nano satellite downlink channel, for the QPSK system, the ACM 6 (coding rate of 0.815) signaling format will achieve the data rate of 162 Mbps, whereas, for the 16-QAM system, the ACM 16 (coding rate of 0.80) signaling format with DPD will achieve the maximum data of 320 Mbps.

5. Conclusions

This paper has presented performance evaluation of X-band nano satellite high-speed downlink system with symbol rate of 100 Msps in practical nano satellite channel. Since general modules with a small, lightweight, and low-power are required for the onboard transmitter, the resulting transmitted signals suffer from severe linear/nonlinear distortion; consequently, effective compensation techniques for nano satellite high-speed downlink system are needed. We have developed a SCCC turbo decoder combined with a SIC turbo equalizer and distortion compensation techniques at the receiver, and a LUT based DPD at the transmitter. The system performance is evaluated by modeling linear/nonlinear distortion sources based on experimental measurements to obtain the modeling output waveform closer to the transmitter EM output. The practical system performances have been obtained by various simulation results.

We have been developing a downlink system for NSC nano satellites, "Hodoyoshi 4". Since different challenging tasks must be solved to complete the downlink system, the simulation results provide design guidelines to obtain suitable LUTs adapting temperature variation at the transmitter and digital signal processing parameters on FPGA at the receiver. The completed transmitter and receiver will be verified by using the nano satellite, "Hodoyoshi 4", and then provide high-speed downlink communications beyond 100 Mbps for future nano satellite applications.

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References

- 1) <http://park.itc.u-tokyo.ac.jp/nsat/main.html>, Jun. 2011.
- 2) Saito, H.: Small satellite REIMEI for aurora observation -five years orbit-, *Proc. International Conference on Space, Aeronautical and Navigational Electronics 2010 (ICSANE 2010)*, SANE 2010-96.
- 3) Nakasuka, S.: From Education to Practical Use of Nano-satellites - Japanese University Challenge towards Low Cost Space Utilization -, *Proc. 8th IAA Symposium on Small Satellite for Earth Observation*, Apr. 2011.
- 4) CCSDS 131.2-B-1: Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications, *ESA, draft blue book*, Mar. 2012.
- 5) Andrews, K. S., Argueta, A., Lay, N. E., Lyubarev, M., Sigman, E. H., Srinivasan, M. and Tkachenko, A.: Reconfigurable Wideband Ground Receiver Hardware Description and Laboratory Performance," *Interplanetary Network Progress Report*, **42** (2010), pp. 1-22.
- 6) Benedetto, S., Garelo, R. and Montorsi, G.: MHOMS, High-speed ACM Modem for Satellite Applications, *IEEE Wireless Commun.*, Apr. 2005, pp. 66-76.
- 7) Calzolari, G. P. and Vassallo, E.: New Coding and Modulation Schemes for Future CCSDS Missions, *TTC 2010*, Sep. 2010.
- 8) Bertinelli, M., Burzigotti, P., Montorsi, G. and Vassallo, E.: ESA Advanced Coding and Modulation Performance under Realistic Channel Conditions, *CCSDS SLS-RFM & SLS-CS WG meeting*, Oct. 2009, SLS-RFM_09-09.
- 9) Iwakiri, N., Tomiki, A., Mizuno, T., Saito, H. and Nakasuka S.: Performance Analysis of SCCC Turbo Equalization with Nonlinear Satellite Channel Compensation Techniques for Nano/Small Satellite High-speed Communication Systems, *Proc. International Conference on Space, Aeronautical and Navigational Electronics 2011 (ICSANE 2011)*, Oct. 2011, SANE-66.
- 10) Iwakiri, N., Saito, H. and Nakasuka, S.: Turbo Equalizer/Decoder Performances of Nonlinear Channels due to Different Classes of GaN HPAs for X-band Nano Satellite High-speed Downlink System," *Proc. International Conference on Space, Aeronautical and Navigational Electronics 2012 (ICSANE 2012)*, Oct. 2012, SANE-71.
- 11) <http://www.synopsys.com/systems/blockdesign/digitalsignalprocessing/pages/signal-processing.aspx>, Jun. 2011.
- 12) Jerichim, M. C., Balaban, P. and Shanmugan, K. S.: *Simulation of Communication Systems*, 2nd ed., Kluwer Academic/Plenum Press, New York, 2000.
- 13) Hagenauer, J.: The Turbo Principle: Tutorial Introduction and State of the Art, *Proc. Int. Symp. on Turbo Codes*, Sep. 1997, pp. 1-11.
- 14) Tkachenko, A.: Wideband Power Amplifier Modeling Incorporating Carrier Frequency Dependent AM/AM and AM/PM Characteristics, *Interplanetary Network Progress Report*, **42** (2010), pp. 1-34.
- 15) Ghannouchi, F. M. and Hammi, O.: Behavioral Modeling and Predistortion, *IEEE Microw. Magazine*, **2** (2009), pp. 52-64.