BANDWIDTH EFFICIENT MODULATION SCHEMES FOR FUTURE TT&C APPLICATIONS

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ABSTRACT

This paper presents initial results of an investigation on bandwidth efficient waveforms for telemetry, tracking and commands (TT&C). Included in the investigation are waveforms that are currently being considered by the International Consultative Committee for Space Data Systems (CCSDS) and American Institute of Aeronautics and Astronautics (AIAA) for standards, advanced waveforms and others that have the potential to become future standards. The goal of this investigation is to recommend a suite of bandwidth efficient modulation schemes for further investigation. This suite of modulation scheme should be suitable for various TT&C applications with data rates ranging from a few hundreds Bit Per Second (bps) to a few hundreds Mega bps (Mbps). First, the philosophy of waveform evaluation is described. The description includes a list of waveform attributes leading to quantitative and qualitative figures of merit for bandwidth efficient waveforms. Then quantitative results for the two most important waveform attributes (bandwidth efficiency and bit error rate performance) are presented. These results will be used by a follow-on study to significantly reduce the number of candidate waveforms, so that all attributes can be more thoroughly evaluated.

KEYWORDS

Improving Use of RF Spectrum, Security/Frequency Allocation, Frequency Encroachment, High Data Rates, Modulation/Multiplexing.

INTRODUCTION

The objectives of the telemetry, tracking and command (TT&C) function of the Air Force Satellite Control Network (AFSCN) are two-fold: (1) to ensure that satellites in its care are injected into the correct orbits, and (2) to ensure that they are positioned in proper locations and maintained in good health throughout their mission duration. Until now AFSCN provides its main service to DoD satellites. Several other satellite control networks have existed to serve other satellites' needs. In particular, Navy, NASA, as well as private organizations have networks in addition to AFSCN. There is an awareness that cost savings can be achieved if an integrated system can serve every satellite's needs. Consequently, there has been increased interest in developing a standardized and interoperable system across military services, NASA, NOAA (National Oceanography Administration Agency) and commercial satellite programs. The desire for interagency cross support (Recommendation 4 in

[OASD 1999]) requires that AFSCN must consider the needs for bandwidth-efficient modulation schemes for TT&C applications for all current and developing satellites. Furthermore, it must also anticipate the modulation schemes that will be utilized by future satellites that are yet to be developed. On the other hand, it is difficult to implement every conceivable modulation scheme in AFSCN. Hence an approach is needed to identify a tractable set of modulation waveforms that will satisfy current and future satellite users and, additionally, provide a database to allow future satellite users to select the schemes that will satisfy their specific TT&C needs. The strong desire for efficient spectrum utilization drives the need for bandwidth efficient modulation (Recommendation 10 in [OASD 1999]). Therefore the eventual goal is to phase out less bandwidth efficient approaches in favor of a small set of highly bandwidth efficient waveforms once the needs of legacy satellites are gone.

Unified S-Band (USB) and Consultative Committee for Space Data Systems (CCSDS) waveforms are generally adopted by non-DoD agencies and commercial satellites. To facilitate interagency cross support, one of the major concerns in the selection of future waveforms for AFSCN applications is the compatibility of the selected waveforms with the USB and CCSDS waveforms. The AFSCN downlink waveforms are compatible with the CCSDS and NASA standards. The problem involves the uplink waveform. Currently, the AFSCN Space-Ground Link Subsystem (SGLS) uplink uses ternary-FSK and is not compatible with USB and CCSDS waveforms. It is highly desirable that future AFSCN waveforms should be able to interoperate with USB and CCSDS waveforms, while at the same time should be easily convertible to SGLS waveform.

The prior effort, Phase 1 of this study [Nguyen 1999], evaluated the waveforms related to AFSCN and NASA-USB uplink operations, namely commanding and ranging. Phase 1 compared SGLS, USB and several other waveforms in terms of performance and spectrum efficiency. The performance attributes addressed were bit error rate (BER) for commanding and range accuracy for ranging. The spectrum efficiency attributes were bounded power spectral density bandwidth, out-of-band rejection, and occupied bandwidth. Phase 1 also addressed the impact of channel bandwidth shrinkage due to the migration of AFSCN uplinks to S-band on the performance of SGLS, USB and other waveforms of interest.

The goal of the current Phase 2 study is to down select the waveforms to a reduced set for further evaluation in Phase 3. This down-selection is based on Phase 1 results in [Nguyen 1999], the Phase 2 analysis in the linear environment (i. e., high power amplifiers operating under back-off conditions) presented in this document, nonlinear BER performance results contained in literature, and our past experience in evaluating waveform performance [Nguyen 1998] [Lui Nov. 1999]. The nonlinear results do not include any assessment of the loss in packing efficiency due to spectral re-growth generated by high power amplifiers operating near saturation.

The next phase, Phase 3, will start with a reduced set of candidate waveforms. It is expected that results from Phase 3 will show that a subset of the waveforms is clearly superior considering all the attributes and the required future needs of AFSCN users. A second down-selection will be made for the final evaluation in Phase 4. This set of waveforms can then be implemented in the future AFSCN, from which a user can select an appropriate waveform. With this in mind, future effort in Phase 4 will involve the generation of performance results and databases on the implemented waveforms to allow a user to make intelligent waveform selections.

ATTRIBUTES FOR EVALUATION

The purpose of this investigation is to identify a set of bandwidth efficient modulation waveforms for future AFSCN use. Toward that end, it is desirable to identify waveform attributes that can lead to figures of merit (FOMs) for evaluating and recommending waveforms. A list of waveform attributes and the rationale for using them in the evaluation process. Twelve waveform attributes have been identified and are listed below. This paper only focuses on the bandwidth efficiency aspect of the waveforms.

1. Bandwidth Efficiency: Since our study focuses on bandwidth efficiency, this is the most important attribute in the evaluation process. The term “bandwidth” in digital communications is rather vague, it can mean many different items, namely, occupied bandwidth, bounded power spectral density bandwidth, necessary bandwidth, noise equivalent bandwidth, and required bandwidth. The bandwidths addressed in this document are:

- Occupied bandwidth.
- Spectral roll-off (bounded power spectral density bandwidth).

The results are presented in Section 4. Alternatively, bandwidth efficiency can be viewed as the ability to pack information into bandwidth, i.e., the amount of data rate (in bits per second) or the number of channels that can be successfully transmitted through a specific frequency band.

2. Power Efficiency: The Bit Error Rate (BER) performance is used as the FOM that provides a good comparison in terms of power efficiency among the modulation schemes under investigation. Of particular interest is the BER performance in an additive white Gaussian noise (AWGN) channel with and without the use of High Power Amplifiers (HPAs) operating at saturation.

3. Upgradibility: The selected waveforms should be easily adaptable to other advanced waveforms that may be used in the future. As spectrum becomes a more precious commodity, it can be anticipated that waveforms, such as M-ary PSK, that are readily extendable to higher order modulation schemes without requiring additional bandwidth are desirable. These waveforms are especially attractive if they can be used with Trellis Code Modulation (TCM) to relax the power requirement.

4. RFI Susceptibility: The following RFI susceptibility characteristics for the recommended waveforms should be evaluated for comparison purposes:

- Adjacent channel tone interference (unmodulated carrier)
- Adjacent channel narrowband or wideband interference (modulated carrier)

5. Equipment Complexities: Recommended waveforms should be implementable with reasonable complexity. Therefore, complexity of the transmitter and receiver for space and ground segments should be evaluated and compared among the waveforms of interest. This should be tempered with the knowledge that what is complex today may not be complex in future years. Issues related to design that impact the users are also addressed. As an example, frequency and phase stability specifications can have a strong impact on hardware design.

6. Backward Compatibility: Backward compatibility with current SGLS waveforms is desirable. This attribute will not be a key factor in the waveform selection process, but it will be noted for reference. Similar to interoperability discussed above, the problem again involves the uplink waveform. Since legacy satellites are expected to be operational well beyond 2010, it is attractive that a future AFSCN waveform can be easily converted to the ternary-FSK SGLS waveform for uplink to these legacy satellites. For example, a BPSK waveform can be readily converted to ternary-FSK when one uses a programmable modem. Otherwise, when using a hardware-only modem, a new or different modulation format or even data rate change usually requires a new modem.

7. Ranging Capability: It is desirable that the recommended waveforms for future AFSCN should be able to perform both ranging and commanding/telemetry functions simultaneously. This capability will avoid the need to utilize a separate waveform to perform ranging. The Phase 2 study has just begun to address this and more study is needed. The recommended waveforms should be able to provide accurate range data in the presence of the transmitted data signal.

8. Signal Acquisition Performance: Signal acquisition performance for the recommended waveforms should be evaluated and compared against the specifications for future AFSCN requirements. Performance for carrier phase and frequency acquisition and re-acquisition will be evaluated for the candidate waveforms.

9. Security: Security issues such as anti-jamming capability should be evaluated.

10. Robustness: The robustness of the recommended waveforms in absorption (or average power reduction) and scintillation environments is of interest. Waveforms are more attractive when their performance degrades more gracefully as scintillation increases. Absorption can only be mitigated by more RF power or antenna gain and will not be addressed in this document. In essence, systems utilizing more robust waveforms have greater availability and reliability. Robustness provides added values to the recommended waveforms.

11. Technology Maturity for Satellite Applications: For the recommended waveforms the requisite technology should be mature. For satellite applications, it is very desirable that the weight and power consumption can be made small.

CHARACTERIZATION OF BANDWIDTH

One of the signal attributes revealed by its power spectral density (PSD) is the amount of occupied bandwidth. Since no real signal is truly band-limited, there are numerous definitions for the bandwidth of a signal. Four commonly used definitions are: i) Occupied Bandwidth, ii) Bounded PSD Bandwidth, iii) Noise-Equivalent (NE) Bandwidth, and iv) Necessary Bandwidth. For this study we have examined the following two bandwidths:

- Occupied Bandwidth – The occupied bandwidth indicates how efficiently the major portion of the signal power can be spectrally contained. To be precise, it is defined as the band that contains 99 % of the power within the band, and leaves exactly 0.5% of the signal power above the upper band limit and exactly 0.5% of the signal the signal power below the lower band limit [Sklar 1988].

- Bounded PSD Bandwidth – The bounded PSD bandwidth describes how successful the unwanted out-of-band radiation is attenuated. It specifies that the PSD, everywhere outside a specified band of frequencies, has fallen to a certain level below the maximum value at the center frequency.

For a typical system, the designer would want to know, for a given modulation format and an associated bandwidth, how well his system can receive a large fraction of signal power while at the same time transmit very little power outside of the bandwidth. A waveform that has a small occupied bandwidth and a small bounded PSD bandwidth should perform well in both aspects. Hence, to a large extent, these two attributes are indicative of bandwidth efficiency.

Using analytical methods and published results, spectral attributes of the candidate modulation formats were investigated. Table 1 summarizes the results for Occupied Bandwidth as well as Bounded PSD Bandwidth at several out-of-band rejection levels. For ease of comparison, all values for bandwidth are tabulated as a multiple of the user data rate, R_d. For modulations that employ spreading codes, bandwidth is tabulated as a multiple of the chip rate, R_{chip}. Chip rate is defined as the user data rate times the spread spectrum processing gain, n, i.e., $R_{chip} = n \cdot R_d$.

Spectral utilization and SFCG (Space Frequency Coordination Group) Mask compliance is also tabulated. Spectral utilization is defined here as the number of data-bits per channel symbol. Modulation formats that satisfy the SFCG spectral mask are highlighted with a shaded background. It is interesting to note that, aside from the continuous-phase modulation (CPM) techniques (MSK, GMSK), only the filtered QPSK and Feher-QPSK modulations are able to comply with the SFCG Mask specifications.

The Occupied Bandwidth results in Table 1 were obtained analytically from closed-form PSD expressions. Cells without values in the “60 dB Roll Off” column were not filled in since the occupied bandwidth is too large to be of interest.

SPECTRUM PACKING EFFICIENCY

Spectrum packing efficiency is expressed in terms of two quantities, namely, number of data link channels that can be packed into a given frequency band and packing efficiency, which indicates the number of bits per second that can be packed into each Hz of bandwidth. Both of these quantities are based on the notion that the modulation scheme that is most spectrally efficient can pack more usable channels and a larger data rate into a given bandwidth, though often at a sacrifice of power efficiency[1].

Figure 1 illustrates a scenario of adjacent signals within a channel bandwidth. The parameter f_c is the carrier frequency of the signal of interest, and Δf is the frequency separation between adjacent signals. For this study, we evaluate the spectrum packing efficiency under the following conditions:

- Without Doppler
- Without spectral re-growth caused by non-linear operation

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[1] A trade-off between bandwidth efficiency and power efficiency is usually performed to select a modulation scheme for a particular application.

- Without coding
- Without baseband filtering for SS-BPSK and SS-QPSK waveforms
- Transmitted interference-to-signal ratio (XISR) = 0 dB
- Channel bandwidth = 4 MHz
- Frequency separation, Δf, is defined in terms of 99 % and 90 % power containment bandwidth

Table 1: Summary Spectral Attributes For Modulation Formats Studied

Modulation Format		Occupied Bandwidth[1]				Spectrum Utilization (Bit/Symbol)	SFCG Mask Compliance
		99.0% Power	At 20 dB Roll Off	At 40 dB Roll Off	At 60 dB Roll Off		
BPSK	Diff. and Coher.	$20.4 \cdot R_b$	$7.4 \cdot R_d$	$64 \cdot R_d$		1	No
Filtered BPSK	Diff. and Coher.	$1.4 \cdot R_b$	$1.24 \cdot R_d$	$1.5 \cdot R_d$		1	No
QPSK	Diff. and Coher.	$10.2 \cdot R_b$	$3 \cdot R_d$	$32 \cdot R_d$		2	No
Filtered QPSK (coh)	r = 0.35	$0.7 \cdot R_b$	$0.9 \cdot R_d$	$0.96 \cdot R_d$		2	Yes
OQPSK	Diff. and Coher.	$10.2 \cdot R_b$	$3 \cdot R_d$	$32 \cdot R_d$		2	No
Filtered OQPSK (coh)	r = 0.35	$0.7 \cdot R_b$	$0.9 \cdot R_d$	$0.96 \cdot R_d$		2	Yes
MSK (coh)		$1.2 \cdot R_b$	$1 \cdot R_d$	$5 \cdot R_d$		1	Yes (<2Ms/s)
GMSK	BT=0.25 BT=0.5	$0.86\ R_b$ $1 \cdot R_b$	$1 \cdot R_d$ $1.2 \cdot R_d$	$1.6 \cdot R_d$ $2.24 \cdot R_d$	$2.12 \cdot R_d$ $2.96 \cdot R_d$	1 1	Yes
π/4-QPSK	Diff. Coher.	$10.2 \cdot R_b$	$3 \cdot R_d$	$32 \cdot R_d$		2 2	No
8-PSK	Coher.	$6.8 \cdot R_b$	$2 \cdot R_d$	$22 \cdot R_d$		3	No
16-PSK	Coher.	$5.1 \cdot R_b$	$1.6 \cdot R_d$	$16 \cdot R_d$		4	No
16-QAM		$5.1 \cdot R_b$	$1.7 \cdot R_d$	$16 \cdot R_d$		4	No
8-FSK	NonCoh.	$7 \cdot R_b$	$7 \cdot R_d$	$64 \cdot R_d$		3	No
16-FSK	NonCoh.	$6.4 \cdot R_b$	$8 \cdot R_d$	$66 \cdot R_d$		4	No
TCM	8PSK 16PSK	$10.2 \cdot R_b$ $6.8 \cdot R_b$	$3 \cdot R_d$ $2 \cdot R_d$	$32 \cdot R_d$ $22 \cdot R_d$		2 3	No
Feher QPSK		$1 \cdot R_b$	$0.9 \cdot R_d$	$1.6 \cdot R_d$	$2.7 \cdot R_d$	2	Yes
QQPSK		$10 \cdot R_b$	$5 \cdot R_d$	$50 \cdot R_d$		4	No
SS/BPSK[2]		$20.4 \cdot R_{chip}$	$7.4 \cdot R_{chip}$	$64 \cdot R_{chip}$		N/A[3]	No
SS/QPSK[2]		$10.2 \cdot R_{chip}$	$3 \cdot R_{chip}$	$32 \cdot R_{chip}$		N/A[3]	No

1. R_b is the raw information bit rate and bandwidths are two sided
2. R_{chip} is the spread spectrum processing gain, n, times the data rate: $R_{chip} = n \cdot R_d$
3. Spectrum Utilization has no meaning when the underlying bits have been transformed to chips

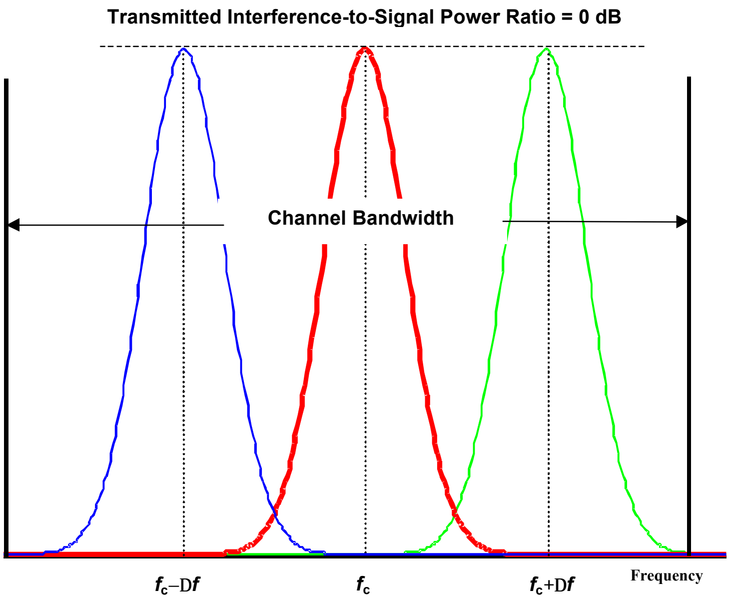

Figure 1: Channel Packing Scenario

The second measure of spectrum packing efficiency is Packing Efficiency (PE) expressed in bits/sec/Hz, which can be expressed as:

$$PE = \frac{R_b \text{ x Number of Signals in 4 - MHz BW}}{4 \text{ MHz}} \qquad (1)$$

Figure 2 presents the packing efficiency evaluated at BER = 10^{-6} for different waveforms in graphical format. The results shown in this figure were computed for waveforms operated in a linear channel, i.e., the power amplifier operated in linear region. It shows clearly that many waveforms have better packing efficiency than the SGLS and USB waveforms. Data for Feher QPSK are subject to verification.

THE IMPACT OF RANGING SIGNAL ON SPECTRAL PACKING EFFICIENCY

A key question in this study concerns the need to include ranging signal in the investigation on spectrum packing efficiency. In order to address this question, this section assesses the impact of Adjacent Channel Interference (ACI) on ranging performance and the mutual co-channel interference between the ranging signal and the command signal. The victim's ranging SNR degradation due to the presence of ACI will be evaluated assuming no filters for the victim and adjacent channels. In addition, the impacts of ranging on command channel will be assessed. In order to simplify the analysis, the following conditions are assumed:

- There is one interferer on each side of the victim spectrum, with interferers spaced equally from victim.
- The interferers have the same waveforms as the victim.

- The SGLS service includes PRN ranging, low rate PCM data, medium rate PCM data, and analog voice.
- The detection bandwidth is much narrower than PRN chipping rate.
- Time, frequency, and phase synchronization are not included.
- The transmitted interference-to-signal ratio = 0 dB.
- The PRN waveform is: 1 MHz chipping rate, modulation index = 0.3 radian.
- The command FSK waveform is: 2 ksps, modulation index = 0.6 radian.
- The data waveform is: 2 ksps at 1.024 MHz sub-carrier, modulation index = 1.0 radian.

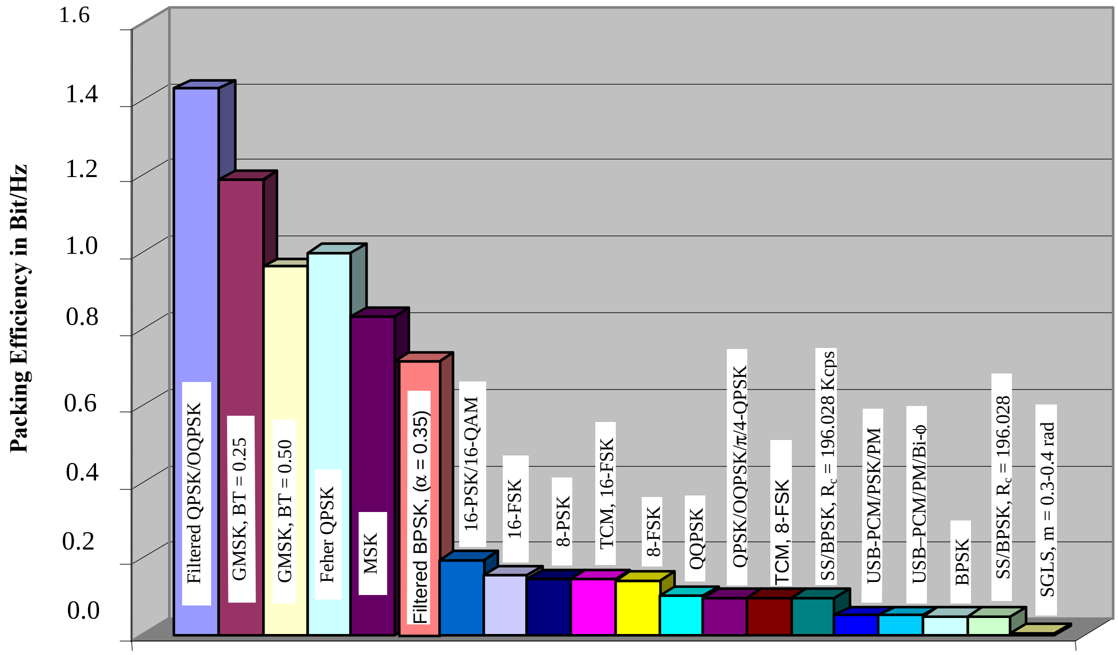

Figure 2 Packing Efficiency for 99% Bandwidth

Figure 3 shows the ranging SNR degradation of the victim channel due to the presence of ACI. The results show that the effects of ACI can be mitigated by increasing the integration time.

Table 2 shows the ranging signal-to-command signal power ratio for various values of ranging and command modulation indices. The interference effects can be ignored for ratios less than –3 dB. It can be seen from Table 5.1 that the ratio can be reduced to less than –3 dB by selecting ranging modulation index to be approximately less than 0.3.

For the three interference effects to be assessed in this section, it can be concluded that:

- The effects of ACI on ranging can be mitigated by increasing the ranging integration time.
- The effects of co-channel command signal on ranging can also be mitigated by increasing the ranging integration time.
- The effects of co-channel ranging signal on command can be made negligible by selecting a small value for the ranging modulation index.

Hence, ranging signal can be ignored in the spectrum packing efficiency investigation as long as the satellite movement over the time of integration is negligible compared to the required ranging accuracy.

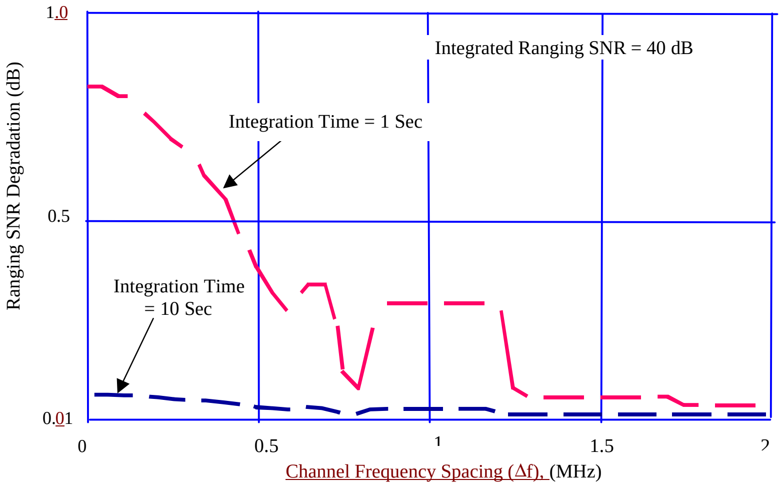

Figure 3: Ranging SNR Degradation Due to Adjacent Channel Interference

Table 2: Ranging Signal-to-Command Signal Power Ratio

Command Modulation Index, rad	Ranging Modulation Index, rad	Ranging Power-to-Command Signal Power Ratio, dB
0.6	0.3	-2.75
1.1	0.2	-10.5
1.1	0.1	-16.5

CONCLUSION

Based on Phase 1 results in [Nguyen 1999], the Phase 2 analysis in the linear power amplifier environment presented in this document, non-linear BER performance results contained in literature, and our past experience in evaluating waveform performance [Nguyen 1998][Lui Nov. 1999], Table 3 presents a suite of waveforms that can be preliminarily recommended for AFSCN. These recommendations are based on strengths and weaknesses in key attributes as well as legacy and future program needs. Stressing environments include interference (hostile and non-hostile) as well as high dynamic environments. The recommended waveforms are grouped into three categories: low, medium and high data rates. The boundary data rate of 4 Kbps between low and medium data rates is based on CCSDS and ISO standards [CCSDS 411.0 B-2]. The boundary data rate of 2 Mbps between medium and high data rates is based on CCSDS division for certain categories of service. Further evaluation will be performed on these waveforms in Phase 3 before a final suite of waveforms can be recommended for implementation in AFSCN.

Table 3 Preliminary Suite of TT&C Waveforms Recommended for AFSCN

Data Rate	**Selected Suite of Modulation Schemes**	
	Benign Environments	**Stressing Environments**
Low Data Rate **5 bps – 4 Kbps**	PCM/PSK/PM-Sine, PCM/PM-Bi-Phase, BPSK*, Filtered BPSK*	SS-BPSK/QPSK
Medium Data Rate **4 Kbps – 2 Mbps**	Filtered BPSK/QPSK/ OQPSK, GMSK, Feher QPSK	SS-BPSK/QPSK (for lower portion of data rate range)
High Data Rate **> 2 Mbps**	Filtered QPSK/OQPSK, Feher QPSK, TCM-Filtered-8PSK/16PSK	

* These waveforms are recommended only for data rates greater than 2 Kbps.

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