ABSTRACT

Most traditional approaches to TT&C have employed waveforms that are neither very power nor bandwidth efficient. A new approach to TT&C waveforms greatly improves these efficiencies. Binary Gaussian Minimum Shift Keying (GMSK) provides a constant envelope bandwidth efficient signal for applications above about 10 Kbps. The constant envelope preserves the spectrum through saturated amplifiers. It provides the best power efficiency when used with turbo coding. For protection against various kinds of burst errors it includes the hybrid interleaving for memory and delay efficiency and packet compatible operations in Time Division Multiple Access (TDMA) environments. Commanding, telemetry, mission data transmission, and tracking are multiplexed in TDMA format.

Key Words

Modulation, coding, bandwidth efficient waveforms, power efficient waveforms, GMSK, turbo coding and interleaving.

INTRODUCTION

The traditional waveforms used for TT&C had their genesis in the 1960’s before digital circuitry became practical for signal generation and reception. The signals typically used for TT&C included subcarrier(s) for modulation for lower data rates and direct modulation with square pulses for higher rates. Often a small amount of residual carrier was provided for synchronization in either case. Under the conditions then existing these approaches served the community well, but perhaps after thirty some years they need to be reevaluated.

At that time frequency management was not a major problem and there was not a strong motivation to conserve the spectrum. However, today the spectrum is very crowded and the number of users as well as desired data rates are increasing rapidly and such subcarrier
signals are not as bandwidth efficient as their direct carrier modulation counterparts. The press for lighter, smaller, more reliable satellites, the constraint of available bandwidth, and the availability of large scale digital signal processing chips have combined to force a reevaluation of the traditional approach in favor of waveforms with higher bandwidth and power efficiency.

Among those waveforms that provide high power efficiency, GMSK modulation is the best candidate for high bandwidth efficiency. To further improve power efficiency, coding can be added and turbo error correction codes provide the highest coding gain of all known codes. Some channel interleaving may be needed for combating multipath and other forms of burst error conditions such as Raleigh fading and interference. There has been some interest in Code Division Multiple Access (CDMA) for interference mitigation and bandwidth efficiency. As a future consideration we could add an optional CDMA or frequency hopping with a significant sacrifice in overall bandwidth efficiency. This increase in bandwidth can be fully offset only when a fully loaded set of simultaneous CDMA or hopped Frequency Division Multiple Access (FDMA) users are operated time synchronously within the same CDMA or frequency hopped channel bandwidth. Figure 1 is a block diagram of the set of signal processing steps needed to fully support a waveform with all these features. The presentations that follow do not included capability for frequency hopping or CDMA and some changes in acquisition and tracking will be necessary when such is added.

**FIGURE 1 TRANSMITTER SIGNAL PROCESSING BLOCK DIAGRAM**

![Diagram](image)

**PERFORMANCE**

Table 1 shows a comparison of the power and bandwidth efficiency for the proposed new turbo coded GMSK TT&C waveform (see line 1) for $10^{-6}$ probability of user bit error ($P_{be}$). It is compared with a similarly coded Feher’s Quadrature Phase Shift Key (FQPSK) modulation and the turbo coded, convolutionally coded and uncoded traditional Binary Phase Shift Key (BPSK) direct carrier modulation. The power efficiency is determined by the minimum required signal Energy per Bit to Noise power density ($E_b/N_0$). The bandwidth efficiency denoted by the Bits per Second to Hertz ratio (Bps/Hz) will drop or alternatively the required channel spacing will increase with stronger adjacent channel signals. Dr. Bow will later show us his GMSK hardware performance data.
MODULATION

There are currently two major contenders for medium to higher data rate (less than 100 Mbps) efficient modulation for TT&C. They are GMSK and FQPSK. GMSK ultimately provides better skirt selectivity for applications in the presence of much stronger adjacent channel signals than will FQPSK while FQPSK is somewhat less complex than GMSK unless one implements them with high integration level Application Specific Integration Circuit (ASIC) technology. The Aerospace Corporation has been actively studying the performance and pursuing the hardware development of a GMSK laboratory test bed for several years.

TABLE 1 PERFORMANCE COMPARISON OF THE PROPOSED RATE 1/2 TURBO CODED GMSK, TURBO CODED FQPSK, TURBO CODED, CONVOLUTIONAL CODED AND UNCODED BPSK WAVEFORMS

<table>
<thead>
<tr>
<th>Modulation and Coding Case</th>
<th>Power Efficiency (Required $E_b/N_o$ in dB at $10^{-6} P_{be}$)</th>
<th>Bandwidth Efficiency (Bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMSK/Rate 1/2 Turbo</td>
<td>3.4 plus Adjacent Channel Interference (ACI) trade with Inter-symbol Interference (ISI)</td>
<td>0.55 and lower depending on modulation BT value related permissible levels of ACI degradation of required $E_b/N_o$.</td>
</tr>
<tr>
<td>FQPSK/Rate 1/2 Turbo Coding</td>
<td>3.4 plus ACI</td>
<td>0.5 and lower depending on adjacent channel interference levels and permissible levels of ACI degradation of required $E_b/N_o$.</td>
</tr>
<tr>
<td>BPSK/Rate 1/2 Turbo Coding</td>
<td>3.25</td>
<td>0.13 and lower depending on ACI levels, filtering and hard limiting considerations</td>
</tr>
<tr>
<td>BPSK/Rate 1/2 K=7 Convolutional Coding</td>
<td>5.5</td>
<td>0.13 and lower depending on ACI levels, filtering and hard limiting considerations</td>
</tr>
<tr>
<td>Traditional BPSK/No Coding</td>
<td>11.1</td>
<td>0.27 and lower depending on ACI levels, filtering and hard limiting considerations</td>
</tr>
</tbody>
</table>

GMSK is a very attractive modulation choice from several perspectives. First, being a member of the Continuous Phase Modulation (CPM) family, it has a constant envelope. The constant envelope is essential for maintaining the spectral envelope when amplifying the modulator output with a hard limiter or a class C (saturated) transmitter. The saturated amplifier will not lead to spectral regrowth that generally occurs when baseband, IF or RF filtering converts some of the BPSK or QPSK phase modulation energy to Amplitude...
Modulation (AM). The saturated amplifier removes that AM and thereby raises the spectral sidebands. GMSK has very steep spectral roll off because of the way it smoothes out the inter-symbol phase transitions. BPSK in theory has abrupt transitions, that lead to high side-band energy levels. GMSK stretches each channel symbol across L symbols where L controls the inter-symbol transition time and thus the amount of inter-symbol interference (ISI) built into the waveform. Second, GMSK closely approximates the performance of BPSK for moderate spectral efficiencies or for more generic spectral efficiencies when high P_{be} levels are allowed as when one uses error correction coding. Strong coding (such as turbo) can reduce the ISI loss to less than 0.2 dB depending on the size of L or conversely how restrictive the bandwidth is. This ISI degrades the E_{b}/N_{o} of the modulation somewhat relative to theoretical BPSK. However Dr. Lui, in a paper that follows shows that for the most part the trellis demodulator equalizes this ISI.

The modulation phase ambiguity can be resolved and the carrier phase estimated for coherent modulation by a sync word contained in each packet transfer frame. This is discussed more in the framing section. An L-1 symbol guard time on each side of the unique word isolates it from data induced inter-symbol interference. The sync word is placed periodically in the stream of data on the downlink and at the beginning of a command block on the uplink. If packet telemetry is used each packet will be preceded by the sync word. A 32 bits sync word will lead to low losses.

ERROR CORRECTION CODING

Our principle investigator on turbo coding is Dr. Charles Wang. His paper will be seen later in this session. Coding is seen as a means of maximizing power efficiency in exchange for some loss of bandwidth efficiency. Turbo coding can provide performance that approaches within 1 dB of the Shannon limit for large block sizes. Dr. Wang has discovered some techniques that mitigate the traditional turbo code P_{be} floor. He will discuss an approach that provides a three order of magnitude reduction of the floor through more carefully matching the tail properties of the code in the decoder.

INTERLEAVING

Interleaving is required whenever there is a potential for channel induced burst errors to degrade the decoder performance. Convolutional and convolutional-like codes work best when noise or interference-induced errors are spread uniformly across a transmission time span that is an order of magnitude or more longer than the error burst. Otherwise, when the noise occurs in bursts the performance is degraded. The interleaver will thereby allow the decoder to work best in spite of the burst errors.
Several types of interleavers exist. They are the traditional block and convolutional as well as the newer helical and hybrid forms. The block interleaver is traditionally used with blocked data such as commands to a satellite or packets of telemetry. However it requires 4 times the memory and has twice the delay as the convolutional interleaver for the same time span of interleaving. The helical interleaver behaves similarly to the convolutional interleaver in these regards. However, the hybrid interleaver, while competitive with the convolutional interleaver on delay and memory for a given time span of interleaving, also has the attraction of the block interleaver in that it operates efficiently with blocks or packets of data. It will allow TDMA of multiple transmitting packet sources into a common receiving node. It also allows long interleaver time spans in the presence of relatively short packets to protect against fading and its attendant burst errors without the need for interleaver flushing when switching transmission among several packet sources. Inter user transmission interleaver flushing is mandatory with the convolutional interleaver under this scenario. All the interleavers must be synchronized using the transfer frame sync word.

**FRAMING AND TRANSFER FRAMES**

The frame structure is TDMA where a set of transfer frame “slots” is assigned to the TT&C functions. The transfer frame includes the data packet preceded by the synchronization word. The data may be a command on uplinks, a telemetry packet on downlinks or for either link the packet may be a tracking sequence. Figure 2 shows such a frame concept. The TDMA approach eliminates the need to use a subcarrier for data in the presence of the tracking PN code. This reduces the spectral and power inefficiency of multiple FDMA carriers or subcarriers for the various functions with their larger required bandwidth. The slots may be operating at different symbol rates, such as very high for tracking while much lower for commands and telemetry. The bandwidth is then driven by the typically higher tracking symbol rate. The sync words within each TDMA slot will provide a reference for carrier phase, phase ambiguity resolution, interleaver sync and decoder block synchronization.

**FIGURE 2. PROPOSED TYPICAL TELEMETRY TDMA FRAMING**

<table>
<thead>
<tr>
<th>Sync Word</th>
<th>Slot i Data</th>
<th>Sync Word</th>
<th>Slot i + 1 Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>• •</td>
<td>• •</td>
<td>• •</td>
<td>• •</td>
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</tbody>
</table>
ENCRYPTION

Encryption is often user vehicle specific. The encryption should be the first feature added to data on transmission, prior to error correction coding, and the last feature removed on reception, after error correction decoding. The sync word is the last item added to the beginning of a transfer frame. It must be sent in the clear in order to be useful for synchronization. Therefore, the encryption should only be applied to the user data or packets.

INTERFERENCE MITIGATION

These waveforms may be used effectively in a CDMA or frequency hopping environment for mitigation of accidental or intentional interference or jamming. Of course the frequency spreading will severely degrade bandwidth efficiency but will mitigate this degradation by permitting multiple simultaneous usage of a band of frequencies by several TT&C applications. This occurs with minimal interference between those applications and will mitigate the external interference to the level provided by the available spreading bandwidth. GMSK with BT less than or equal to 0.2 will provide the best bandwidth efficiency of all known binary modulations types that mutually occupy the band allocation while still minimizing ISI loss. If the interfering signals have power level differences greater than one or two dB at a receiver, frequency hopping will provide better interference mitigation without major ACI loss for a closely stacked set of FDMA users. Otherwise CDMA may be better.

CONCLUSIONS

Dr. Gee Lui is the principle investigator on the theory and analysis of GMSK. He and Dr. Kuang Tsai will discuss the spectral and $E_b/N_0$ performance followed by a discussion of the trellis and linear receiver. Dr. Tien Nguyen and Mr. John Charroux will present the work on phase tracking techniques. Dr. Lui and Kuang Tsai will discuss their work on symbol and carrier phase synchronization. Dr. RT Bow has built a laboratory breadboard model using Field Programmable Gate Array (FPGA) technology. Finally Dr. Charles Wang will discuss his work on the use of a relatively short block turbo code for TT&C. Their work will follow in that order.

When you have heard all the papers in this session you should have a clearer understanding of the reasons why turbo coded Binary GMSK with hybrid interleaving provides the best bandwidth efficiency subject to a 0.5 dB loss from BPSK. Hybrid interleaving, TDMA framing, frequency hopping and encryption, when needed will round out a superior general purpose TT&C waveform.