HIGH–DATA–RATE COMMUNICATION TECHNIQUES FOR SMALL SATELLITES

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Abstract

Modulation and coding techniques that are both power- and bandwidth-efficient are examined at the system level in this paper. Such techniques include convolutional encoding with QPSK modulation and the relatively new trellis-coded modulation. Power and bandwidth trade-offs are discussed, a sample link calculation is given, and hardware implementation is considered.

Introduction

This paper examines modulation and coding techniques suitable for high–data-rate communication links from small satellites. High data rates (>50 megabits/s) are inherent in certain spacecraft imaging instruments. Such rates allow the rapid transmission of data to ground stations and may eliminate the need for tape recorders on some missions. With these rates, however, come some special considerations for the communication link. Spacecraft links are usually power-limited but not bandwidth-limited (i.e., plenty of channel bandwidth is available at lower data rates). At higher data rates, however, the link also becomes bandwidth-limited because of the relatively narrow channel allocations in popular frequency bands. Thus, we require transmission techniques that are both power- and bandwidth-efficient—a somewhat unique problem for spacecraft.

Several approaches to the high–data-rate problem are considered. The brute force approach of increasing transmitter power is examined first and is shown to be undesirable for small satellites. Conventional forward error correction (FEC) techniques are discussed next. Such techniques are widely used and are very power efficient; however, they increase the transmitted bandwidth. Finally, a relatively new FEC technique known as trellis-coded modulation (TCM) is proposed for use on small satellites. This technique is both power- *and* bandwidth-efficient and represents an attractive solution to the high–data-rate problem. This paper discusses the salient system-level features of TCM, provides a sample link calculation, and addresses hardware implementation.

Conventional Approaches

Transmitter data rates for low–Earth-orbiting (LEO) spacecraft have historically been relatively low (typically between a few kilobits/s and a few megabits/s). Links for LEO spacecraft transmitters are straightforward to implement and can typically be accomplished at S-band with a 3-watt transmitter and a low-gain antenna.

For higher data rates, however, more effective isotropic radiated power (EIRP), which can be realized by increasing the transmitter power and/or using a high-gain antenna, is required. Increasing the transmitter power is undesirable because of the associated increases in DC power, weight, and cost, whereas improving the antenna gain is a better solution if the radio frequency (RF) is high enough to maintain a small aperture size. Some frequency bands, however, have a limit on the power density allowed at the Earth's surface to prevent interference with terrestrial microwave systems. This constraint places an upper limit on the EIRP.

An attractive alternative to the brute force approach discussed above is to add forward error correction (FEC) consisting of a simple convolutional encoder on the spacecraft and a Viterbi soft decision decoder on the ground. This approach is used widely on spacecraft systems today because it has minimal impact on the spacecraft, ground station hardware is readily available, and the coding gain is significant (see Table 1). The primary disadvantage is that the transmitted RF bandwidth is increased owing to the extra coding symbols. For example, the popular rate-1/2 code doubles the RF bandwidth.

Table 1. Convolutional FEC Characteristics.

Code Rate	Coding Gain (dB)* ($P_e = 10^{-6}$)	RF Bandwidth Expansion
1/3	5.7	3:1
1/2	5.5	2:1
3/4 (punctured)	4.2	1.33:1
7/8 (punctured)	3.1	1.14:1
1/1 (no coding)	0.0	1:1

*With Viterbi soft-decision decoding. Values are typical of commercially available hardware with constraint length k = 7. P_e = probability of error.

At high data rates, the transmitted RF bandwidth becomes a significant concern. For example, in the popular X-band region, some channel allocations are only 40- to 100-MHz wide. Thus, the satellite link will become both power- and bandwidth-limited. It would therefore be desirable to use an FEC technique that conserves both power and bandwidth.

Trellis-Coded Modulation Approach

Trellis-coded modulation is an FEC technique that provides significant coding gain without expanding the RF bandwidth. This advantage is realized because TCM extends the signalling alphabet to the next higher level and integrates the coding and modulation functions. For example, trellis-coded 8-ary phase-shift keying (8PSK) would replace uncoded quaternary phase-shift keying (QPSK). Trellis-coded modulation was developed during the 1980's for high-speed voiceband modems and has also been proposed for use in narrowband satellite transponder channels such as FLTSATCOM.[1] Recent technology advances have made TCM decoder chips available for use in high–data-rate satellite links.

The integral relationship of the coding and modulation is the key element allowing TCM to achieve significant coding gain. The encoding algorithm is designed to maximize the squared Euclidean (geometric) distance between the transmitted symbol sequence and all possible erroneous received sequences. The encoding algorithm, therefore, is tailored to the signalling constellation being used in contrast to conventional FEC techniques, which maximize the Hamming distance (number of symbols in which two sequences differ) between the transmitted sequence and all possible erroneous received sequences. In the latter case, the encoding algorithm is independent of the modulator being used. For a more detailed description of the inner workings of TCM, consult References 2 and 3.

Figure 1 shows a block diagram of one possible encoder/modulator for an 8PSK system using TCM. The input data stream is first demultiplexed into two symbol streams. One symbol stream enters the 8PSK modulator unaltered. The other stream enters a rate 1/2 convolutional encoder and is converted into two parallel symbol streams, which enter the 8PSK modulator. The symbol rate into the 8PSK modulator is the same as it would be for uncoded QPSK; therefore, the RF bandwidth has not been expanded. At the receiver, the signal is demodulated, and a TCM decoder uses the Viterbi algorithm to determine the most likely transmitted symbol sequence. Significant coding gain can be achieved. For 8PSK–TCM, the coding gain is about 4 dB with respect to uncoded QPSK.* In general, TCM coding gain is specified in relation to the next lower level of signalling alphabet. For example, a 16PSK–TCM system will have a coding gain of about 4 dB relative to uncoded 8PSK.

In addition to providing coding gain without expanding the RF bandwidth, TCM can also be used to *reduce* the RF bandwidth and maintain good power efficiency at the same time. For example, suppose we wish to transmit our signal in a bandwidth less than that of uncoded QPSK. As a first step, we could use uncoded 8PSK instead of QPSK. To improve the power efficiency, we could then convert the uncoded 8PSK signal into a 16PSK–TCM signal. This conversion will yield some coding gain and maintain the same transmitted bandwidth as that of uncoded 8PSK.

*Coding gains given in this paper apply at a probability of error (P_e) of 10^{-6} and assume a 64-state encoder (constraint length k = 7). See References 2 and 3 for more details on achievable coding gain.

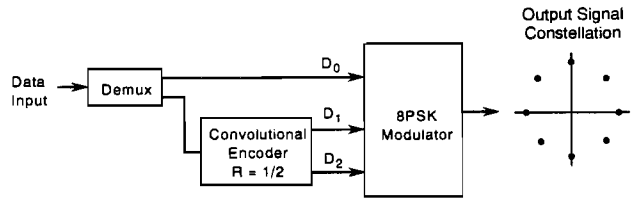

Figure 1. Example of an Encoder/Modulator for 8PSK–TCM.

Figure 2 summarizes the energy and bandwidth performance of several candidate modulation schemes. The figure includes uncoded schemes (QPSK, 8PSK, 16PSK), conventionally coded schemes (QPSK with convolutional code rates 1/2 through 7/8), and TCM schemes (8PSK–TCM and 16PSK–TCM). Modulation schemes that involve an amplitude-modulated component, such as 16-ary quadrature amplitude modulation (16QAM), are not included because they are not suitable for transmission through the nonlinear power amplifiers typically used on spacecraft. We see that QPSK with code rate 1/2 results in quite a large transmitted band-

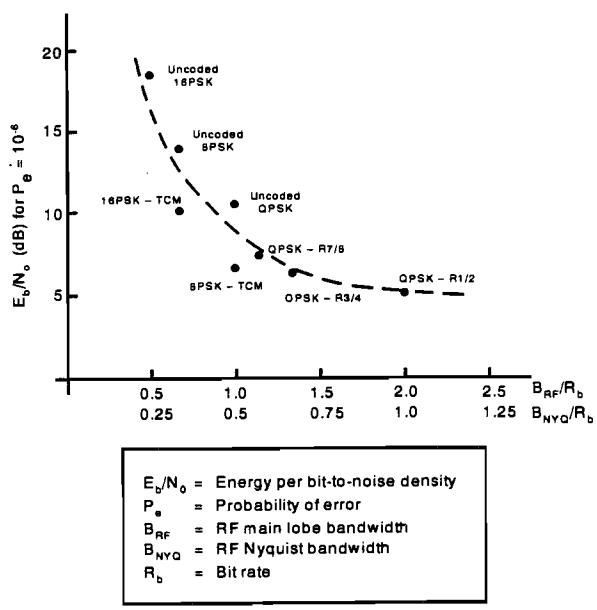

Figure 2. Power and Bandwidth Performance of Modulation Schemes.

width but yields only a slight improvement in energy efficiency over the rate 3/4 code. At the other extreme, we see that uncoded 16PSK has quite a small bandwidth but requires 8 dB more energy than uncoded QPSK. The schemes that are most attractive for high–data-rate communications lie between B_{RF}/R_b values of 0.6 and 1.5. A separate abscissa scale is provided to indicate the minimum theoretical RF bandwidth if Nyquist filtering is used. In practice, a transmitter filter would be used to limit the RF signal bandwidth to somewhere between the two scales.

Link Calculation

Table 2 presents a sample link calculation for a 150-megabit/s link from low-Earth orbit. The frequency is at X-band to keep the spacecraft antenna small. The modulation scheme is 16PSK–TCM, which keeps the main lobe of the transmitted signal within a 100-MHz channel bandwidth. Filtering can be employed to reduce the transmitted bandwidth further. The link makes use of a 1-watt transmitter and an 8-inch parabolic dish on the spacecraft. Note that the dish antenna has a relatively narrow beamwidth and must be pointed towards the ground station, either by slewing the spacecraft or gimballing the antenna. A similar link using uncoded QPSK would have approximately the same power efficiency but would require a channel bandwidth of 150 MHz to pass the main lobe of the RF signal.

Table 2. Sample Link Calculation.
(Orbit altitude = 500-km circular, frequency = 8.5 GHz, data rate = 150 megabits/s, modulation = 16PSK–TCM.)

Parameter		Value
Spacecraft transmitter power:		30.0 dBm
Spacecraft passive loss:		–3.0 dB
Spacecraft antenna gain:		+21.0 dBic
EIRP:		48.0 dBm
Path loss:	(10° elevation)	–175.6 dB
Atmospheric loss:		–0.5 dB
Polarization mismatch loss:		–0.5 dB
Pointing loss:		–0.4 dB
Rain fade:		–1.5 dB
Ground antenna gain: (10-m dish)		+56.0 dBic
Total received power:		–74.5 dBm
Ground system noise temperature:		316 K
Ground system noise density:		–173.6 dBm/Hz
Data rate:		81.8 dBHz
Noise power in bandwidth = date rate:		–91.8 dBm
E_b/N_o received:		17.3 dB
E_b/N_o required (16PSK–TCM, $P_e = 10^{-6}$):		10.1 dB
Implementation loss:		–3.0 dB
Link margin:		4.2 dB

Hardware Implementation

We have thus far examined the system-level aspects of both conventional FEC and TCM schemes. Fortunately, in both cases the hardware on the spacecraft is much less complex than the hardware on the ground. The critical technology issues are the size and weight of the encoder/modulator and the speed of the Viterbi decoder.

The technology required to implement high-rate convolutional encoders and QPSK modulators on spacecraft is generally available. High-speed, radiation-tolerant logic, such as Fairchild Advanced CMOS Technology (FACT) and emitter-coupled logic (ECL), can be used for the encoder. QPSK modulators with good phase and amplitude balance are available in small hermetic packages. These devices can be converted to vector modulators for TCM schemes if the I and Q inputs are driven by analog instead of discrete signals. Figure 3 shows a potential TCM encoder/modulator design. The outputs of the convolutional encoder address a look-up table implemented as a high-speed programmable read-only memory (PROM) or programmable logic array (PLA). Stored in this table are appropriate values of I and Q for each encoder state. These values are converted to analog levels that drive the vector modulator. The basic design can be adapted to any two-dimensional modulation scheme (8PSK, 16PSK, 16QAM, etc.). Another attractive feature is that phase and amplitude imbalances in the vector modulator can be compensated for in the look-up table, resulting in a very accurate multiphase modulator. This feature is particularly important because multiphase systems are highly susceptible to phase and amplitude imbalances.

On the ground end, QPSK demodulators and Viterbi decoder chips have found widespread application in satellite communications. The limiting factor is the speed of the decoder chip, which currently tops out at about 25 megabits/s. This limitation, however, can be overcome by connecting multiple chips in parallel. An 8PSK or 16PSK demodulator is inherently more complex than a QPSK demodulator because it must deal with synchronization and demodulation of a multiphase signal. This complexity, however, does not represent a real technology barrier as evidenced by existing

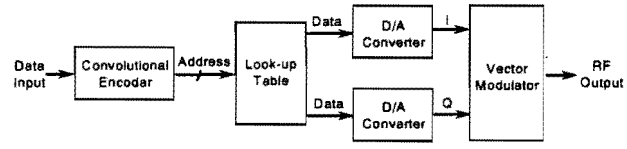

Figure 3. Potential TCM Encoder/Modulator Design.

equipment such as terrestrial microwave radios that demodulate high-rate QAM signals. A recent discussion of multiphase demodulator implementation can be found in Reference 4. High-rate TCM decoder chips, available just within the past year, can be used with the multiphase demodulator.* These chips make use of a slightly suboptimal technique that permits their use with both 8PSK and 16PSK signalling constellations. The speed of the chips is limited to 60 megabits/s (for 16PSK–TCM); therefore, more than one chip may need to be connected in parallel to achieve higher rate operation.

Conclusion

This paper has examined the system-level and hardware aspects of high–data-rate communication techniques for small spacecraft. Such systems must be both power- and bandwidth-efficient. Conventional FEC techniques (QPSK modulation with convolutional coding) are suitable as long as bandwidth expansion is allowable. Trellis-coded modulation techniques (using multiphase signalling constellations) provide an attractive alternative if the transmitted RF bandwidth is a critical issue.

*Qualcomm Model Q1875 pragmatic trellis decoder chip.

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