3 A cross-layer interaction between TCP and physical layer

It is possible to optimize the performance of TCP over satellite links without changing the TCP behavior, by operating on transmission parameters. We examine here how TCP performance can be improved by trading packet loss rate with bottleneck link bandwidth. This procedure does not interfere in any way with the normal behavior of the TCP stack, but instead requires appropriate capability of automatic tuning of the link parameters at the physical level.

For a given available radio spectrum, antenna size and maximum transmission power, the selections of modulation scheme, symbol rate and FEC type allow a usually wide range of choices. Commonly used wireless systems make such design choices in a static fashion, by possibly permitting the user to manually change some of them, or in some cases by dynamically switching between a limited number of preset parameters. Even in those cases where a wide range of IBR (information bit rate) values is available, the criterion to switch between them is only dependent on the perceived channel quality [2]. For terrestrial wireless, an example is the IEEE 802.11 standard, where it is possible to dynamically change the modulation and coding schemes [3]. The reason to hop among different sets of parameters is that most wireless links have highly variable physical characteristics: satellite links for example are subject to variable atmospheric attenuation of the signal; low and medium earth orbit satellite constellations suffer from variable signal attenuation due to changing slant path, blocking due to obstacles in the line of sight, multipath fading and changing satellite distance; indoor systems greatly suffer from interference from similar systems in addition to all the previous reasons.

Traditional internet lore assumes that packet error rate should be as low as possible for TCP to perform well [4]: a common rule of thumb is to engineer the link so that packet error rate due to link errors is negligible with respect to the error rate caused by congestion. However, this need not be the case, as shown in [5]. This finding opens the possibility for researching adaptive algorithms that dynamically choose the optimal channel parameters (e.g. modulation and coding) with the aim of maximising the TCP performance.

In 1997, many authors realized that a simple and elegant formula could link the steady-state performance of TCP to its segment loss rate [6]. The formula connects the maximum throughput on an unlimited bandwidth channel with the segment size *MSS*, the round trip time *RTT* and the segment loss rate q:

$$throughput = K \frac{MSS}{RTT\sqrt{q}} \qquad \text{for } q < 1\% \qquad (9.3)$$

where K is a constant equal to 1.31 in the case of random segment losses without delayed acknowledgements. Subsequently, (3) was modified to take into account the TCP behavior in the presence of timeouts [7], thus allowing for a greater accuracy at higher PER, resulting in:

$$throughput = \frac{MSS}{RTT\sqrt{\frac{2bq}{3}} + RTO\min\left(1, 3\sqrt{\frac{3bq}{8}}\right)q(1+32q^2)}, \quad (9.4)$$

where b is the number of segments acknowledged by each ACK.

Lakshman and Madhow, in [8], proposed a method for computing the TCP goodput in band-limited channels.

In [9] it is shown that it is possible to obtain a better performance for a single TCP connection by jointly choosing the PER and IBR of satellite links that maximize its throughput computed at the end user (*goodput*), and [10] analyses the case for multiple TCP connections.

The basic concept is that for a given wireless transmission system, it is realistic to assume that some of the parameters are dynamically tunable, so that the channel PER can be traded for IBR (information bit rate). For example, it is possible to change the modulation scheme, thus reducing the channel bit rate, in order to obtain a higher bit energy to one-sided noise spectral density ratio E_b/N_0. The modulation scheme can be changed together with the FEC (forward error correction) to have a wider range of choices and to exploit as much as possible the available radio spectrum. Most modern transmission systems provide for variable bit rates by changing the FEC redundancy used, some of them for each individual packet. By using rate-compatible punctured convolutional codes [11] it is even possible to seamlessly change the FEC, that is, while maintaining bit time synchronization of the data stream.

As far as the modulation scheme is concerned, let us consider a satellite carrier modulated at a rate of S symbols/s. We consider the widely diffused M-ary PSK or QAM (quadrature amplitude modulation) types. In these modulation schemes, M is the number of points, in the phase-amplitude space, relative to the constellation of the modulated symbols. Typical values of M are 2, 4, 8, 16, 32, and 64; BPSK and QPSK schemes correspond to M values of 2 and 4, respectively.

FEC types come in a multitude of flavors, often concatenated between them. We define the coding rate r as the inverse of the coding redundancy. For example, in the case of a (255, 223) Reed-Solomon code concatenated with a 1/2 convolutional code, the resulting r is 223/(255*2) = 0.437.

The information bit rate, i.e. our bottleneck rate B, is given by

$$B = S\, r\, \log_2 M;$$

for a given channel condition C/N_0, a modulation scheme with M points and a coding rate r, the operating E_b/N_0 expressed in dB is given by

$$E_b / N_0 = C / N_0 - 10 Log_{10} B;$$

diagrams similar to the one shown in figure 9.1 are used to estimate the PER.

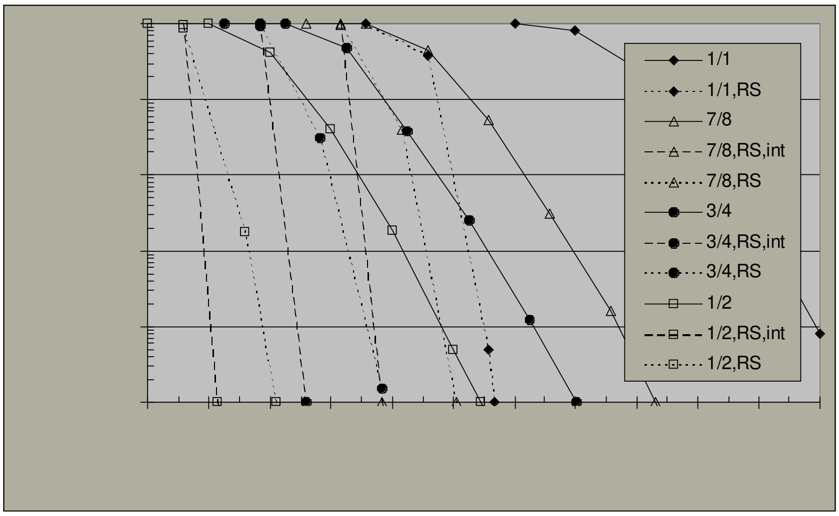

Figure 9.1: Combinations of concatenated codes.

For each C/N_o, the PER is a function of M and r. Since the TCP goodput depends on B and q, it is possible to find M and r that maximize the goodput for each given C/N_o. The way the goodput depends on B and q can be evaluated using an analytical expression, such as (9.3) or (9.4), where q is set equal to the PER, or by means of simulation or experimental measurements.

As an example, figure 9.2 shows the goodput achievable by considering two modulation schemes, namely BPSK (M=2) and QPSK (M=4) and four coding schemes, all based on the standard NASA convolutional coding with constraint length 7, with code rates r=1/2 (base code), r=3/4 (punctured base code), *r*=7/8 (punctured base code), *r*=1 (no coding). Four curves are depicted, each for a different C/N_o. Each curve represents how the TCP goodput changes as a function of the information bit rate, i.e., the bottleneck rate *B*. For each channel condition, an optimum combination of parameters exists which gives the maximum TCP goodput.

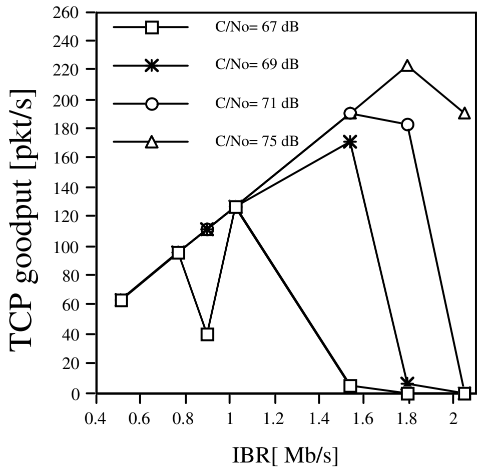

*Figure 9.2: Goodput of a single NewReno TCP connection vs. the available information bit rate for different C/N_o values. Packet size = 1 kB, S =1.024 Msymbol/s, bottleneck buffer size = delay*bandwidth of a GEO link.*

The above discussion leads to the conclusion that satellite systems could benefit from adaptive algorithms for choosing the transmission parameters. The recent DVB-S2 standard [12] considers very powerful error-correcting codes, such that an optimisation based on channel coding would be useless because the curves that give the packet error rate versus Eb/No are so steep that we have a sort of on-off behaviour of the physical channel: either the PER is negligible, or it is so high that it collapses TCP performance. However, when a satellite return channel is used [1], optimisation on the return channel could be useful.

An additional possibility is to insert a link-layer erasure code [13], [5] just above the MAC layer, which could be an all-software solution, independent of the underlying hardware characteristics.

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