Reliable Multicast via Satellite: Uni-directional vs. Bi-directional Communication

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Abstract

We investigate reliable multicast communication over satellite networks. We compare a scenario where receivers can use a feedback channel to signal loss to a scenario where no feedback channel is available. We show that the introduction of a feedback channel is the key to allow for bandwidth-efficient, robust, and fully reliable multicast communication via satellite.

Keywords: Satellite, Reliable Multicast, Error Control, FEC, ARQ, Feedback channel

1 Introduction

The use of satellite systems becomes more and more attractive and feasible due to reduced costs and advances in technology. With the deployment of several global satellite networks, satellite communication will soon be ubiquitously available. Satellite networks are a natural broadcast medium providing high data rates [1][2], and are therefore well suited to any kind of multicast communication.

Unfortunately, satellite links suffer from relatively high bit error rates compared with todays terrestrial fiber trunks. While in the Internet packet loss is assumed to happen mainly due to congested routers, in wireless networks interference is the origin of most lost or damaged packets. Error recovery is therefore a very important issue with regard to reliable multicast communication where all data is reliably delivered to all receivers [3]. Two techniques of error recovery are well known: Automatic Repeat reQuest (ARQ) where lost *packets* are retransmitted, and Forward Error Correction (FEC) where so called *parity* (or redundancy) *packets* are sent along with the original packets to recover potential loss [4]. While ARQ requires a feedback channel, FEC does not.

In this paper, we investigate the importance of the availability of a feedback channel to guarantee full reliability and efficient bandwidth usage for multicast communication. In Section 2, we present our scenarios and assumptions. In Section 3, the numerical results of an evaluation of our scenarios with regard to bandwidth usage are explained. The paper is concluded in Section 4.

2 Model

2.1 The service

We investigate the reliable transfer of an application data unit (ADU) of size f, which can be a file, for instance, from one source to a number of r receivers. For the transfer the ADU is segmented into N packets of size s. Reliable transfer hereby means that all N packets must be delivered to all r receivers. The definition of reliability will be relaxed by introducing a **residual error probability** α expressing that at least one receiver may not receive at least one packet. Full reliability therefore means that $\alpha = 0$.

2.2 The scenarios

We examine two scenarios, for each of which transmission is performed via a standard geostationary satellite. For more information about the characteristics of our example satellite see the appendix.

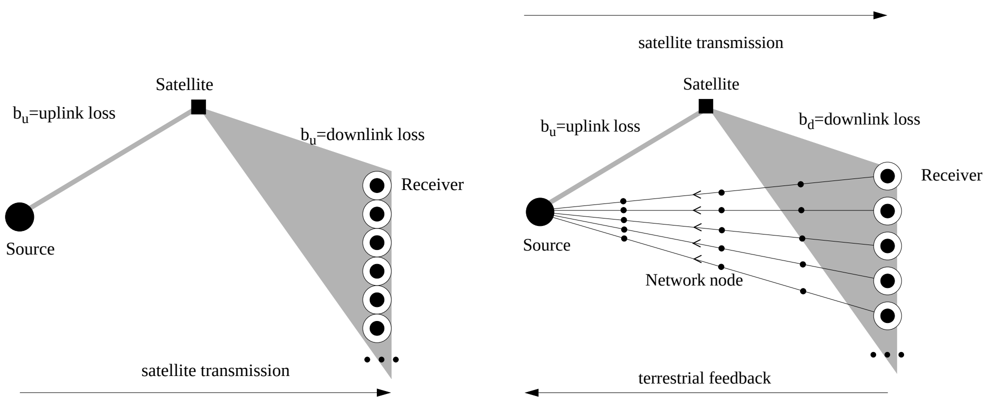
In **Scenario FEC**, the r receivers are not able to communicate back to the source. This means that they can not signal the loss of a packet. Any ARQ protocol is therefore not adequate and FEC [5] becomes the only technique to deal with loss. Our recovery protocol is the following: the N packets are sent in so called **transmission groups** (TG) consisting of k original packets and h parity packets that are derived from the original packets by using a Reed-Solomon-Coder [6]. The receiver can deliver all k packets of a transmission group to its application when at least k out of the total number of $n = k + h$ packets have been received. It does not matter which out of the $k + h$ packets arrive, but only how many. Losses of original packets are recovered using parity packets. One parity packet thereby can recover the loss of a different packet at different receivers. This scenario can never guarantee full reliability, but only a reliability of $1 - \alpha$, since there will always be a residual probability that less than k packets arrive. Since the bit error rate may vary over time, Scenario FEC also has to cope with the difficulty of how to dynamically select the right value for the number of parity packets h per TG to achieve a given residual error probability.

In **Scenario HY**, there exists a terrestrial feedback channel allowing the receivers to send feedback messages to the source. This gives us the possibility to use a more sophisticated error recovery protocol that has proven to be a scalable and bandwidth efficient reliable multicast protocol [5]. This protocol is a hybrid ARQ type 2 protocol that combines ARQ and FEC, and works as follows: original packets at the source are arranged in transmission groups of initially k packets. For every transmission group a sufficient[1] number of parity packets h is coded and stored. The source sends initially only the k original packets per TG. Receivers indicate the source how many packets for a particular TG are lost. The source then sends as many parity packets as necessary (the maximum number packets lost by any receiver) belonging to the corresponding

[1] We assume that an infinite number of parities is available.

TG. That means, all packets retransmitted are *parity packets*, original packets are sent only once at the beginning. The receiver begins to decode as soon as he has k packets – no matter if parity or original packets.

An illustration of the two scenarios is given in Figure 1. The Scenarios are taken from [7].



(a) Scenario FEC (b) Scenario HY

Fig. 1. Scenarios

2.3 The loss model

The source is sending packets of size s via the **uplink** to the satellite in the sky where the packets are forwarded via the **downlinks** to the r receivers on the earth. There is no coding or decoding in the satellite, i.e. the satellite just acts as a repeater.

The probability that a bit is damaged and unrecognizable (corrupted) is called **bit error rate** b. The bit error rate is assumed to be constant over the time of a transfer session. We assume that bit errors happen independently from each other (no burst loss), which will give us an upper bound on the packet loss probability. A whole packet is assumed to be lost when at least one bit is damaged. The packet loss probability p is hence dependent on the packet size s and can be calculated by $p = 1 - (1 - b)^s$. We distinguish **packet loss on the uplink** occurring with probability p_u and **packet loss on the downlinks** occurring with probability p_d. A packet that is lost on the uplink will be lost for all receivers, a packet lost on a downlink will be lost for only one receiver. Due to stronger antennas, the bit error rate is normally lower on the uplink than on the downlink. For reasons of simplicity, we assume that the bit error rate on uplink and downlink are the same.

Current satellite systems normally use FEC on link level to detect and correct bit errors (Viterbi codes, Reed-Solomon codes). Link level FEC is implemented in hardware and its *parameters* are adjustable only by the satellite provider. We assume that link level FEC is completely turned off (we will discuss later why).

Our Reed-Solomon-Coder/Decoder that produces and decodes the parity packets is located in the end-systems at the sender and the receivers, and is implemented in software [4]. The Reed-Solomon-Coder/Decoder deals with *erasures* only. For each packet there is a checksum to detect bit errors (corruptions). A corrupted packet is then thrown away, i.e. turned into an erasure.

2.4 The impact of rain

Rain causes an attenuation between $8dB$ and $10dB$ for frequencies between $12GHz$ and $14GHz$ [8], [9]. This increases the bit error probability b by a factor between 10 and 200. We examine rain on the uplink as well as rain for a certain percentage of downlinks. For our evaluations, we model rain by increasing the bit error rate b by two orders of magnitude on either uplink or downlinks.

2.5 The performance measure

We compare the two Scenarios with regard to the bandwidth they use. The expected bandwidth usage $E[B]$ is represented by the total number of packets sent divided by the number of data packets sent. For **Scenario FEC** $E[B]$ corresponds to the relationship of the sum of data and parity packets to the data packets per transmission group, hence:

$$E[B_{FEC}] = (k + h)/k \tag{1}$$

The parameter k is thereby freely adjustable by the source. The number of parity packets h is calculated in dependence of the reliability required. The **degree of reliability** $\Im$ is defined as the probability that every receiver receives every packet (i.e. the whole file). Let α be the residual error probability expressing that at least one packet is lost for at least one receiver. The degree of reliability $\Im$ is then $\Im = 1 - \alpha$.

One packet arrives at all receivers when it is not lost at the uplink and not lost at any downlink. A packet can be reconstructed when at least k out of the $k + h$ packets sent arrive at all receivers. The exact formula to calculate the reliability can be found in the Appendix.

For **Scenario HY** we compute the expected bandwidth usage $E[B_{HY}]$ via simulation in Matlab. $E[B_{HY}]$ expresses the relationship between the sum of all original packet k and all retransmitted parity packets $E[M]$, and the original packets k. The number of original packets k per transmission group is again a parameter to be chosen by the source, the value of the random variable M denoting the number of parities transmitted is a result obtained from the simulations of the protocol described above. A complete transmission round is repeated 1000 times to smooth the results.

$$E[B_{HY}] = (k + E[M])/k \tag{2}$$

Later we will use the expression **bandwidth gain**. We define bandwidth gain for Scenario X over Scenario Y as:

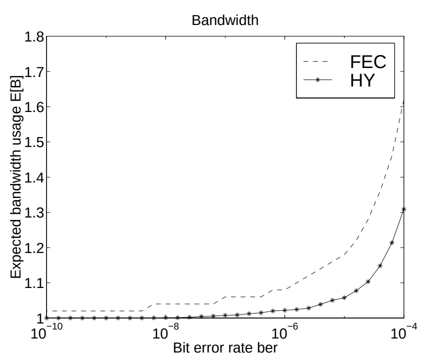
$$B_{gain_X} = E[B_Y]/E[B_X] \tag{3}$$

3 Numerical Results

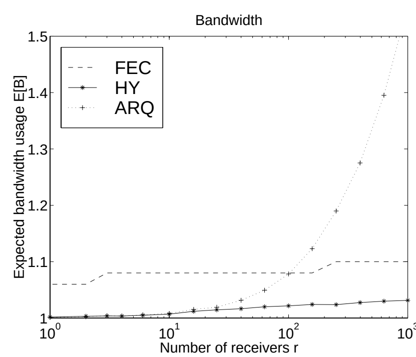
3.1 Influence of communication parameters

We consider the transfer of a file of length f to r receivers for a given bit error rate b on the uplink and the downlinks. File size f, number of receivers r, and bit error rate b are considered to be parameters that are fixed for a session. By contrary, packet size s, number of original packets k per TG, and the residual error probability α for Scenario FEC can be adjusted. The residual error rate of Scenario FEC will be $\alpha = 10^{-4}$ for all experiments if not indicated differently. For Scenario HY this parameter is always $\alpha = 0$, i.e. *full reliability* is assured for all receivers.

In Figure 2(a), we see the impact of the bit error rate b on the bandwidth usage $E[B]$ for both scenarios. For any bit error rate b the needed bandwidth $E[B]$ is significantly higher for Scenario FEC than for HY. The bandwidth gain of Scenario HY is even growing with the bit error rate b.



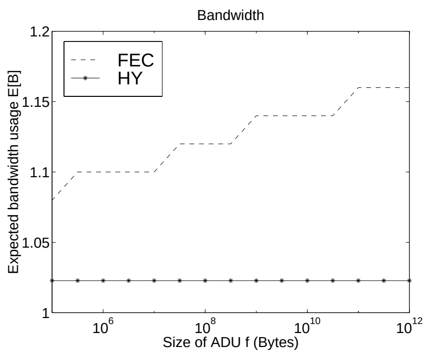
(a) Bandwidth usage varying bit error rate b: $r = 100, \alpha = 10^{-4}, f = 100KBytes, s = 100Bytes, k = 50$.



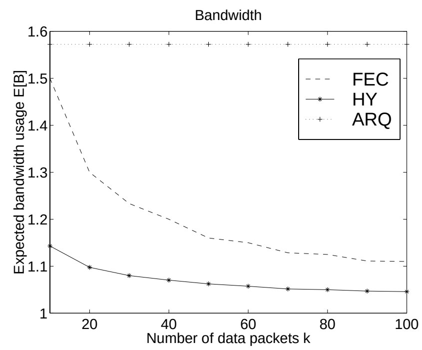
(b) Bandwidth usage for varying number of receivers: $\alpha = 10^{-4}, b = 10^{-6}, f = 100KBytes, s = 100Bytes, k = 50$.

Fig. 2. Bandwidth usage for varying bit error rate and number of receivers

When we vary the number of receivers r as in Figure 2(b), Scenario HY is superior for the whole range of r. The reason for that phenomena is the different information available at the sender for the two scenarios: while Scenario FEC can calculate only the *expected value* of the packets lost, Scenario HY receives feedback about the number of packets lost and therefore knows the *exact number* of packets lost. In order to meet the given reliability, Scenario FEC needs to send more parity packets than may actually be needed. We see that even a simple ARQ, where lost original packets are retransmitted, protocol achieves better bandwidth usage for up to $r = 100$ receivers. However, Scenario FEC scales much better for a growing number of receivers r.



(a) Bandwidth usage for varying ADU size f: $b = 10^{-6}, r = 100, s = 100 Bytes, k = 50$.



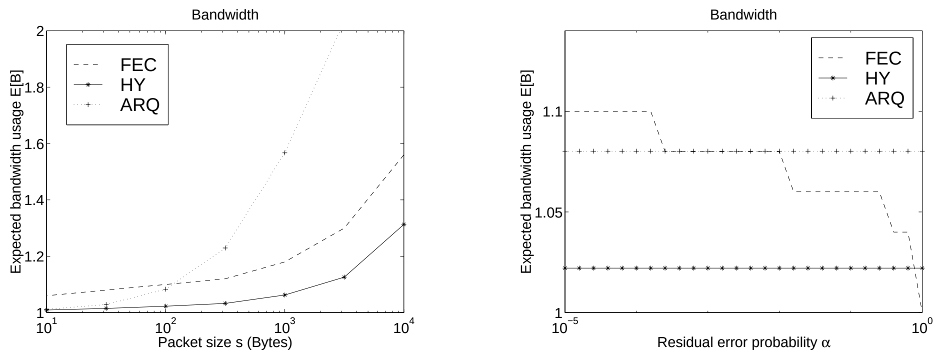
(b) Bandwidth usage for varying number of data packets k: $b = 10^{-6}, \alpha = 10^{-4}, r = 100, f = 100 KBytes, s = 1KB$.

Fig. 3. Bandwidth usage for varying ADU size and TG size

A very interesting result can be seen in Figure 3(a). In order to achieve a reliability of $1 - \alpha$ for Scenario FEC, the need for adding parity packets h per transmission group (TG) and hence the bandwidth usage per packet is growing with the size of the file f. In contrary, for Scenario HY the bandwidth usage per packet is independent of the size of the file f. This is due to the fact that Scenario FEC depends on probabilistic calculations. For every TG there is still a residual error probability. The more TGs are send, the higher the residual error probability α for the whole file, and the more parities must be coded. By contrary, for Scenario HY the residual error probability of the whole file is not affected by the residual error probability of the TGs since we have always $\alpha = 0$.

For the number of original packets k per TG, we can see in Figure 3(b) that for both scenarios a high TG size k yields higher efficiency. The results for a simple ARQ protocol – which does not know TGs – is depicted additionally. For

Scenario FEC, high TG sizes are much more important than for Scenario HY, which is largely insensitive to k. The bandwidth gain for Scenario HY is much higher for small TG sizes k. Both curves are converging towards 1 for infinite k.



(a) Bandwidth usage for varying packet size s (overhead 5 Bytes): $b = 10^{-6}, r = 100, f = 100KBytes, k = 50$.

(b) Bandwidth usage for varying residual error rate α: $b = 10^{-6}, r = 100, f = 100KBytes, s = 100Bytes, k = 50$.

Fig. 4. Bandwidth usage for varying packet size and residual error probability

We now investigate the influence of the packet size s on bandwidth usage $E[B]$. The effect of the packet size s can be seen in Figure 4(a). The larger the packet size s, the higher the bandwidth usage $E[B]$ for all scenarios including a simple ARQ protocol. Since we have assumed that bit errors occur independently, this is due to the fact that the smaller the units of loss (packets), the less data is needed to repair the loss. Assume that one bit is corrupted: for a packet of size $s = 10Bit$ only $10Bits$ must be repaired, for a packet of size $s = 100Byte$ all $100Bytes$ are lost.

We already said that with Scenario FEC no full reliability can be achieved. We therefore defined the residual error probability α, which was $\alpha = 10^{-4}$ in all experiments before. In Figure 4(b) we see what happens when the residual error probability α is varied for Scenario FEC. The bandwidth usage $E[B]$ for Scenario FEC decreases rapidly with the reliability constraint. However, to achieve the same bandwidth usage $E[B]$ for $r = 100$ receivers as Scenario HY, the residual error probability is at least $\alpha = 0.5$, which cannot be called reliable multicast anymore. To reach the bandwidth efficiency of a simple ARQ scheme, still a residual error probability of more than $\alpha > 10^{-3}$ must be accepted.

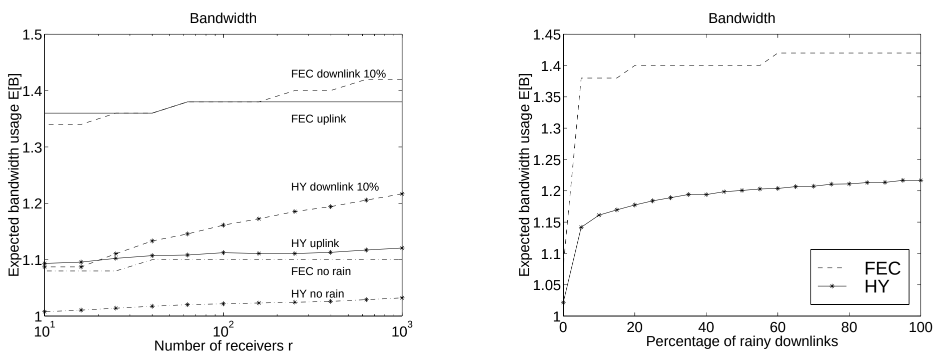
We could see that for all parameters considered, the Scenario HY shows better bandwidth efficiency than Scenario FEC. Even a simple ARQ scheme performs better for a small number of receivers. Only by largely relaxing the reliability constraint, the same bandwidth usage could be achieved as in Scenario HY. We saw for Scenario HY that a wide range of packet size and transmission group size lead to efficient bandwidth usage.

3.2 Influence of rain

Rain may concern the uplink from the source to the satellite or the downlinks from the satellite to the receivers. There are two problems concerning rain on the downlink: first, the source has no knowledge about the rain (rain on the uplink is at least visible) and how many and which receivers are concerned. The second problem is the problem of heterogeneity. Some receivers may experience no loss or low loss, while the receivers affected by the rainy downlinks suffer from high loss rates.

In Figure 5(a) we see what happens when the bit error rate is increased by two orders of magnitude due to rain. Rain on the uplink as well as on 10% downlinks causes for both scenarios a significant increase of the bandwidth usage. But for Scenario FEC the impact of rain is stronger than for Scenario HY compared with the case of no rain.

The influence of loss on the uplink is independent from the number of receivers r. This explains why the number of receivers r has a stronger impact on the bandwidth usage for rain on a constant percentage of downlinks than for rain on the uplink.



(a) Bandwidth usage for uplink rain for varying number of receivers: $\alpha = 10^{-4}, b = 10^{-6}, b_{rain} = 10^{-4}, f = 100KBytes, s = 100Bytes, k = 50$.

(b) Bandwidth usage for downlink rain for varying percentage of rainy downlinks: $\alpha = 10^{-4}, b = 10^{-6}, b_{rain} = 10^{-4}, f = 100KBytes, s = 100Bytes, k = 50$.

Fig. 5. Scenario with Rain

It is interesting that rain for only 10% of the downlinks has a worse impact on bandwidth usage $E[B]$ than rain on the uplink although uplink loss concerns all receivers. On the other hand we can see in Figure 5(b) that the bandwidth does not increase a lot with the percentage of rainy downlinks for both scenarios. This two effects are due to the specific characteristic of a satellite network: a packet lost on the uplink, is lost for all receivers. One parity packet is sufficient for all receivers to repair one loss on the uplink. Loss on a downlink concerns only one receiver, for all other receivers the parity packet sent is useless and causes waste of bandwidth.

So far we have assumed for the Scenario FEC that the source knows the bit error rates b_u and b_d and adjusts the amount of parities accordingly to achieve a target α. In reality this is typically not the case. Figure 6 shows that assuming a wrong value for the bit error rate b has a disastrous impact on the reliability $\Im$. An increase in the bit error rate by only one order of magnitude can decrease the reliability from almost $\Im = 1$ to almost $\Im = 0$.

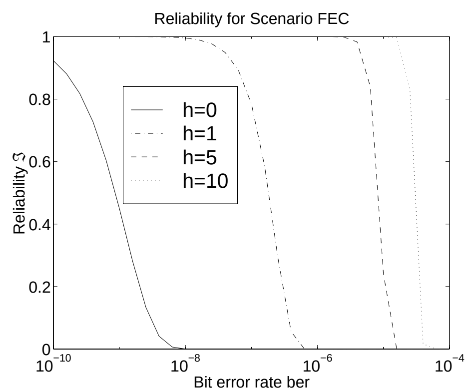


Fig. 6. Reliability for Scenario FEC varying bit error rate b: $r = 1000, f = 100KBytes, s = 100Bytes, k = 50$.

Since correct estimations of the bit error rate b are difficult and wrong values lead either to high losses or bandwidth waste, Scenario FEC seems not to be well suited for reliable multicast communication when a high number of receivers is involved.

4 Conclusion

We compared reliable multicast transmission over satellite links for a scenario without a feedback channel and a scenario with a feedback channel when using state-of-the-art error control protocols. We could see that for all cases the feedback scenario was more bandwidth-efficient than the no-feedback scenario. It also guarantees 100% reliability whereas the no-feedback scenario provides reliability only with a certain probability. The most serious problem of a scenario without feedback channel is the need for parameter estimation (bit error rate): To allow for a stable communication of high reliability under unknown loss conditions will often lead to wasting bandwidth unnecessarily. Scenario HY that uses a hybrid error control protocol with feedback adapts automatically to changing parameters. It does not need any parameter estimation. This makes it robust against high bit error rates due to rain and a high number of receivers. We therefore conclude that the introduction of a feedback channel is the key prerequisite for reliable multicast via satellite.

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A Satellite Communication Parameters

We consider a standard geostationary satellite with the following characteristics:

- The Equivalent isotropic radiated power of the sending earth station: $EIRP_{ES} =$ 70 dB(W)
- The operating frequency of the sending earth station: $f_u = 14$ GHz
- The bandwidth of earth station and receiver is $W = 72$MHz

- Atmospheric wave attenuation on up- and downlink: $L_A = 0.3$ dB
- The figure of merit of the satellite receiving antenna: $(G/T)_{SL} = 6.3\,\mathrm{dB}(K^{-1})$
- The EIRP of the satellites sending equipment: $EIRP_{SL} = 43.6$ dB(W)
- The operating frequency of the sending satellite: $f_d = 12$ GHz
- The figure of merit of the earth station receiving antenna: $(G/T)_{ES} = 26.2$ dB(K^{-1})
- Earth station and satellite can send with a data rate between $R_{min} = 1Mbit/s$ and $R_{max} = 40Mbit/s$
- The calculations of the carrier power-to-noise spectral density C/N_0 yield: $(C/N_0)_u = 97.2dB(Hz)$ and $(C/N_0)_d = 91.8dB(Hz)$.
- The corresponding bit error rates depend on the used data rate R. Using coherent QPSK encoding and demodulation (no FEC), the calculations give a bit error rate for the uplink between $1.0 \cdot 10^{-6} \geq b_u \geq 2.7 \cdot 10^{-10}$. The same calculations for the downlink yield $1.8 \cdot 10^{-5} \geq b_d \geq 4.3 \cdot 10^{-9}$.

B Calculation of Reliability for Scenario FEC

In this section, we derive the formula to calculate the probability for Scenario FEC that all r receivers receive a file of size f without any corruption. The file is split into N packets of size s, i.e. $f = Ns$, and sent in transmission groups (TGs) of n packets including k original and $h = n - k$ parity packets.

A packet is assumed to be lost when at least one of its s Bits is corrupted. Given the bit error rate b_u on the uplink, the probability that a packet is lost between earth station and at the satellite is hence $p_u = 1 - (1 - b_u)^s$, for the downlink accordingly $p_d = 1 - (1 - b_d)^s$ per receiver. The probability that all receivers receive a *certain packet* when no FEC is used is hence $\Im(r, p_u, p_d) = (1 - p_u)(1 - p_d)^r$. The reliability that all receivers receive the complete file of size $f = Ns$ when no FEC is used is then

$$\Im(s, N, r, b_u, b_d) = [(1 - b_u)^s (1 - b_d)^{sr}]^N \tag{4}$$

The reliability can also be expressed in dependence of f by

$$\Im(f, r, b_u, b_d) = [(1 - b_u)(1 - b_d)^r]^f \tag{5}$$

Things are getting more complicated when FEC is used. It is no longer necessary that every single packet arrives correctly, but at least k out of the $n = k + h$ packets sent per TG. This can be expressed using the cumulative *Binomial Distribution*: the probability that an arbitrary TG arrives at the satellite is $\sum_{i=k}^{n} \binom{n}{i} (1 - p_u)^i p_u^{n-i}$. The probability that this TG arrives at all the r receivers depends on how many packets arrived at the satellite: let $i \geq k$ out of n packets arrive at the satellite, then at least k out of the i packets must arrive for all r receivers. Since the file is divided in N/k TGs, the reliability that all N/k TGs arrive at all r receivers is

$$\Im(k,n,s,N,r,p_u,p_d) = \left[\sum_{i=k}^{n}\binom{n}{i}(1-p_u)^i p_u^{n-i}\left(\sum_{j=k}^{i}\binom{i}{j}(1-p_d)^j p_d^{i-j}\right)^r\right]^{N/k} \tag{6}$$

or expressed as a function of the bit error rates:

$$\Im(k,n,s,N,r,b_u,b_d) = \left[\sum_{i=k}^{n}\binom{n}{i}(1-b_u)^{si}(1-(1-b_u)^s)^{n-i}\left(\sum_{j=k}^{i}\binom{i}{j}(1-b_d)^{sj}(1-(1-b_d)^s)^{i-j}\right)^r\right]^{N/k} \tag{7}$$