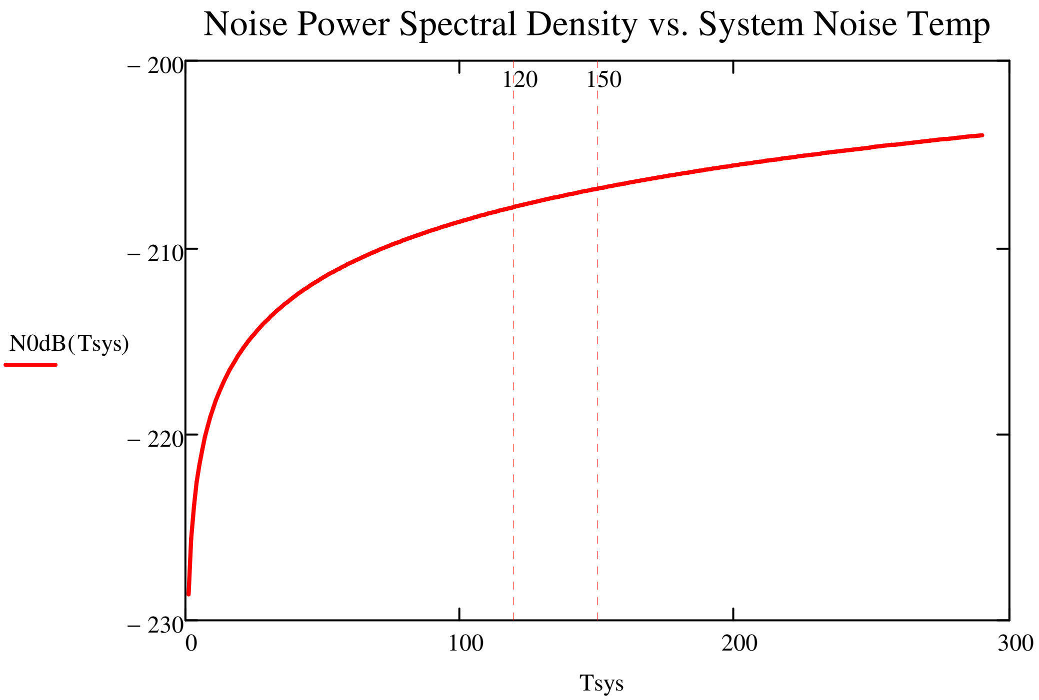
Microwave Engineering Project Link Analysis

version 3.4
22 July 2008
by W5NYV, KA9Q, KB5MU

$k := 1.3806503 \cdot 10^{-23}$	Boltzmann's constant.
$Tsys := 0, 1 .. 290$	System noise temperature.
$N0dB(Tsys) := 10\log(k \cdot Tsys)$	Noise power spectral density in dB



Receive noise temperature in the expected range of 120K to 150K gives the following spectral noise densities in dB.

$N0dB(120) = -207.807 \times 10^{0}$

$N0dB(150) = -206.838 \times 10^{0}$

$EbN0 := 3$ Required Eb/N0 for the rate 1/2 K=7 (255, 223) code.

$N0dB := -206, -207 .. -208$ Noise power spectral density range of interest given 150 > Tsys > 120

$SpacecraftTransmitAntennaGain := 18$ dB

$NamasteReceiveAntennaGain := 22.43$ dB

$SpacecraftTransmitLosses := 3$ dB

$NamasteReceiveLosses := 3$ dB

$PathLoss := 195.13$ dB

For the case of 20W RF power available at the spacecraft, calculate the achievable downlink data rates.

$SpacecraftTransmitPower := 20$ Watts

$PowerAtSpacecraftTransmitAntenna := 10 \cdot \log(SpacecraftTransmitPower, 10) - SpacecraftTransmitLosses$

$PowerAtSpacecraftTransmitAntenna = 10.01 \times 10^{0}$ Power at antenna in dBW

$EIRP\_20W := SpacecraftTransmitAntennaGain + PowerAtSpacecraftTransmitAntenna$

$EIRP\_20W = 28.01 \times 10^{0}$ EIRP in dBW

$RxFlux\_20W := EIRP\_20W - PathLoss$

$RxFlux\_20W = -167.12 \times 10^{0}$ Received power flux in dBW

$RxPower\_20W := RxFlux\_20W + NamasteReceiveAntennaGain - NamasteReceiveLosses$

$RxPower\_20W = -147.69 \times 10^{0}$ Assuming 20W RF power at spacecraft, 18dB gain at spacecraft, 195dB path loss, 3dB of transmit losses, 3dB of receive losses, and 22dB gain at ground station. This is receive power in dBW.

$\text{BRdB\_20W(N0dB)} := \text{RxPower\_20W} - \text{N0dB} - \text{EbN0}$ Bit rate in dB assuming 20W spacecraft RF power.

$\text{BR\_20W(N0dB)} := 10^{\left(\frac{\text{BRdB\_20W(N0dB)}}{10}\right)}$ Bit rate in Hz assuming 20W spacecraft RF power.

For the case of 50W RF power available at the spacecraft, calculate the achievable downlink data rates.

$\text{SpacecraftTransmitPower} := 50$ Watts

$\text{PowerAtSpacecraftTransmitAntenna} := 10 \cdot \log(\text{SpacecraftTransmitPower}, 10) - \text{SpacecraftTransmitLosses}$

$\text{PowerAtSpacecraftTransmitAntenna} = 13.99 \times 10^{0}$ Power at antenna in dBW

$\text{EIRP\_50W} := \text{SpacecraftTransmitAntennaGain} + \text{PowerAtSpacecraftTransmitAntenna}$

$\text{EIRP\_50W} = 31.99 \times 10^{0}$ EIRP in dBW

$\text{RxFlux\_50W} := \text{EIRP\_50W} - \text{PathLoss}$

$\text{RxFlux\_50W} = -163.14 \times 10^{0}$ Received power flux in dBW

$\text{RxPower\_50W} := \text{RxFlux\_50W} + \text{NamasteReceiveAntennaGain} - \text{NamasteReceiveLosses}$

$\text{RxPower\_50W} = -143.71 \times 10^{0}$ Assuming 50W RF power at spacecraft, 18dB gain at spacecraft, 195dB path loss, 3dB of transmit losses, 3dB of receive losses, and 22dB gain at ground station. This is RF flux in dB.

$\text{BRdB\_50W(N0dB)} := \text{RxPower\_50W} - \text{N0dB} - \text{EbN0}$ Bit rate in dB assuming 50W spacecraft RF power.

$\text{BR\_50W(N0dB)} := 10^{\left(\frac{\text{BRdB\_50W(N0dB)}}{10}\right)}$ Bit rate in Hz assuming 50W spacecraft RF power.

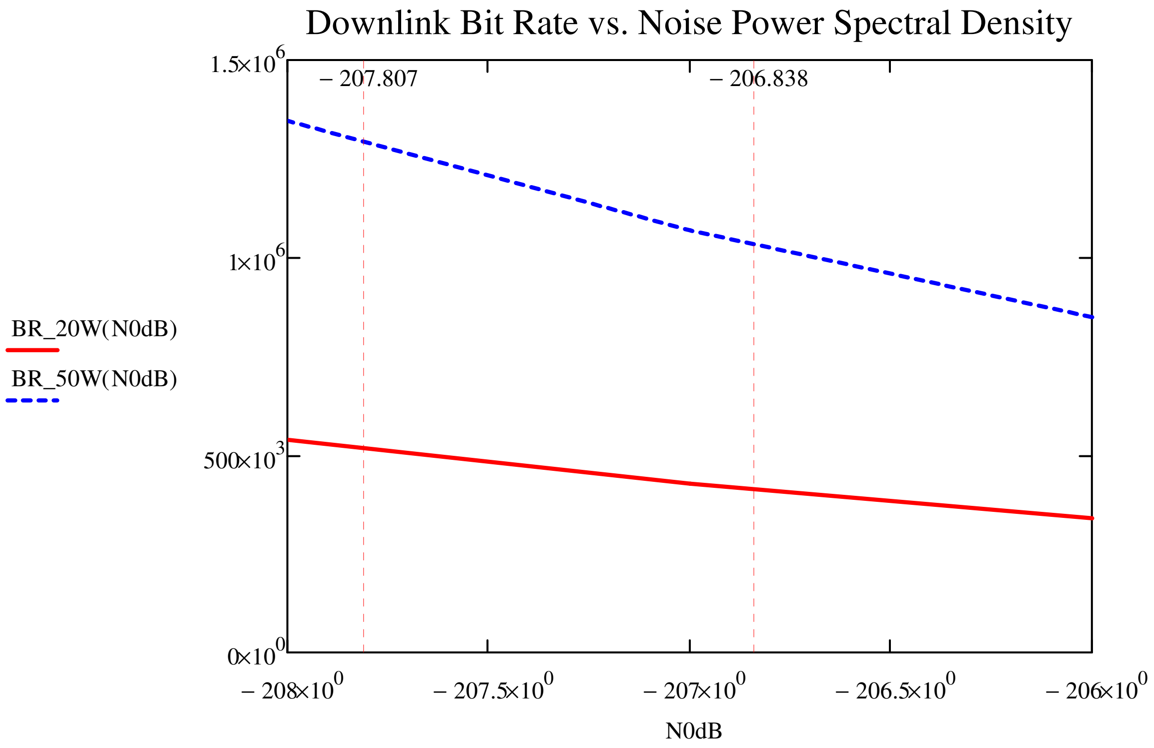
Marked on the graph below are the data rates expected given receive system noise temperature range of 150K to 120K, and RF power range of 20W and 50W RF at spacecraft, 18dB antenna gain at spacecraft, 3dB of transmit losses, 3dB of receive losses, and 22dB of antenna gain on the ground.

At 150K, the 20W bit rate is $BR\_20W(-206.838) = 411.936 \times 10^{3}$

At 120K, the 20W bit rate is $BR\_20W(-207.807) = 514.908 \times 10^{3}$

At 150K, the 50W bit rate is $BR\_50W(-206.838) = 1.03 \times 10^{6}$

At 120K, the 50W bit rate is $BR\_50W(-207.807) = 1.287 \times 10^{6}$



Receive

Receive bandwidth is 3400-3410 MHz.

A simple evaluation of the capacity of the downlink is as follows. Assume 15kHz per user for voice. This includes a generous amount for a quality vocoder as well as the overhead for that vocoder. 15kHz per user goes into the various data rates to give various capacities.

At 150K, the 20W capacity is $\frac{\mathrm{BR\_20W}(-206.838)}{15000} = 27.462 \times 10^{0}$ users.

At 120K, the 20W capacity is $\frac{\mathrm{BR\_20W}(-207.807)}{15000} = 34.327 \times 10^{0}$ users.

At 150K, the 50W capacity is $\frac{\mathrm{BR\_50W}(-206.838)}{15000} = 68.656 \times 10^{0}$ users.

At 120K, the 50W capacity is $\frac{\mathrm{BR\_50W}(-207.807)}{15000} = 85.818 \times 10^{0}$ users.

Transmit - 8ary FSK

Transmit bandwidth is 10MHz located within 5650-5670 MHz.

For a bit rate of 15kbps, using 8ary FSK, that is 5ksymbols/second. Every three bits is represented as one tone. In order to maintain orthogonality using noncoherent modulation, the 8 tones must be separated by the symbol rate, so each user takes 40kHz of bandwidth [(8 tones)(5kHz)]. This rate can be halved with coherent modulation, for a result of 20kHz.

Coherency means that the phase of each tone has a fixed phase relationship with respect to a reference. This means that transitions from tone to tone must be phase continuous. This means that the frequency differences between the tones and symbol rate must be interrelated. The frequency differences between the tones is called the shift.

A synchronous FSK signal which has the shift equal to an exact integral multiple of the keying rate in bauds is the most common form of coherent FSK. Coherent FSK has superior error performance. Noncoherent FSK is simpler to generate. Noncoherent FSK has no special phase relationship between consecutive elements.

$M := 8$ Set the order of the modulation.

$data\_rate := 15 \cdot 10^3$ Set the data rate.

$bits\_per\_symbol := \log(M, 2)$

$bits\_per\_symbol = 3 \times 10^0$ Obtain bits per symbol.

$$symbol\_rate := \frac{data\_rate}{bits\_per\_symbol}$$

$symbol\_rate = 5 \times 10^3$ Obtain the symbol rate.

$noncoherent\_bandwidth := symbol\_rate \cdot M$

$noncoherent\_bandwidth = 40 \times 10^3$ Minimum noncoherent modulation bandwidth required.

$$coherent\_bandwidth := symbol\_rate \cdot \frac{M}{2}$$

$coherent\_bandwidth = 20 \times 10^3$ Minimum coherent modulation bandwidth required.

$uplink\_bandwidth := 10 \cdot 10^6$ Set the uplink bandwidth available.

$$uplink\_noncoherent\_capacity := \frac{uplink\_bandwidth}{noncoherent\_bandwidth}$$

$$\text{uplink\_noncoherent\_capacity} = 250 \times 10^{0}$$

Maximum uplink voice capacity for noncoherent modulation case.

$$\text{uplink\_noncoherent\_capacity} := \frac{\text{uplink\_bandwidth}}{\text{coherent\_bandwidth}}$$

$$\text{uplink\_noncoherent\_capacity} = 500 \times 10^{0}$$

Maximum uplink voice capacity for coherent modulation case.

Frequency hopping with M-ary FSK was suggested in order to provide a spread spectrum CDMA alternative for analysis. On PACSAT, multiple receivers and FSK modulation was a good choice because of the short aquisition time. It was a simple noncoherent method to achieve multiple access.

Phil KA9Q writes:

"There is no question that simple TDM or FDM provides greater capacity than CDMA when each source generates data at a steady, predictable rate. You simply divide up the total resource according to the data rates and you're done.The difficulty comes when your data sources are numerous and bursty, with rapid and unpredictable changes in the offered data rate. Voice users are a classic example of such a user population.

Unless the system capacity is so great that everyone who may ever use the system can have a dedicated fraction of it enough to handle their peak offered traffic, a TDM or FDM system requires some sort of dynamic capacity allocation. This mechanism can be either centralized or distributed, but it must be present.

Allocation mechanisms can run on various time scales. It might allocate capacity for a telephone call or ham QSO lasting several minutes on average. Or it might try to allocate capacity more quickly, on each exchange or perhaps every syllable.

Especially in a satellite system, propagation delays can seriously impair the efficiency of rapid allocation scheme. If the traffic bursts are less than a round trip time, as they often are with voice syllables, dynamic allocation becomes impossible. You have to do your allocations on longer time scales and sacrifice the gains that a quicker scheme might provide.

The big advantage of CDMA is that it eliminates the need for explicit dynamic capacity allocation. Each user transmits when it has something to send and it stops emitting RF (or drops to a very low level) when it has no data. This can happen very rapidly, even on

> every vocoder frame if desired (typically 20-30 milliseconds). This is much faster than the round trip delay of a satellite at geostationary altitude. The savings here may well exceed the multiuser interference inherent with CDMA. They certainly do in terrestrial cellular networks, which is why CDMA has been such a success.
>
> The logical form of spread spectrum for almost any amateur application would be frequency hopping due to its inherent tolerance of uncontrolled narrow band interference. It also has much less stringent requirements on transmitter power control than direct sequence. The logical modulation method to go with frequency hopping is M-ary FSK. Frequency hopping involves phase noncoherence with each hop, so a modulation that can be efficiently demodulated non coherently has an advantage. M-ary FSK is the obvious choice here as it could work with as little as one FSK symbol per hop. It is also constant envelope, and easily generated with a DDS. (The DDS would do the modulation and the spreading in one operation.)
>
> Another possibility is differentially demodulated BPSK, though each hop would have to last for some number of bits. Now I am not saying that the capacity gains from CDMA would necessarily be worth the extra complexity in our specific application. We may find that dynamic capacity allocation on slower scales may be perfectly adequate. But I would at least like to see it considered and analyzed."

First, let's consider the classic frequency hopping FSK (frequency shift keying) system. The information sequence, which is the data we want to transmit, is input to an encoder. Encoders usually do forward error correction and add things like preambles, which are often used to make demodulation easier. The encoded information sequence then goes to a frequency shift keying modulator, which turns the encoded information sequence into its corresponding tone sequence. The output of the FSK modulator is fed to a mixer, which mixes the tone sequence (our information source prepared as an FSK signal) with a sine wave of varying frequency. The varying frequency is a function of a pseudorandom number generator (PN Gen on the block diagram). The output of the mixer is bursts of FSK data that hop around to different frequencies at particular time intervals.

A PN generator has the qualities of a random number source while remaining deterministic. In other words, the PN generator creates the signal that will make our information hop around seemingly at random, but if we set up a corresponding and synchronized PN generator on the receiver side, then we can figure out the exact hopping sequence. If we mix the received signal with this corresponding PN generator, we get our FSK sequence back. After doing FSK demodulation, we get our information sequence back.

There is an extra block in the receiver called Time Sync. This is necessary because the PN generator at the receiver must be synchronized with the PN generator at the transmitter. There are at least two ways to do this.

In this particular example, the rate that we hop around is much slower than the symbol rate. You can tell this by where the PN sequence enters the system. It is after the modulation and before demodulation. A typical application is to hop after some number of symbols have been transmitted.

The sort of system that Phil is talking about above hops around at a faster rate.

The definition of fast vs. slow hopping varies slightly depending on which book you refer to. Generally, though, if the hopping rate is equal to or slower than the symbol rate, it's considered slow hopping. If the hopping rate is equal to or faster than the symbol rate, it's fast hopping. We started out thinking of hopping at the symbol rate, which would be at a frequency of 5kHz for a 15kHz channel.

The first question considered was how often to assign a channel, which is equivalent to assigning a hopping sequence. The extremes are assigning a hopping sequence every frame to assigning a hopping sequence to every user. The reasonable selections of how to assign hopping frequency are somewhere in between. The first case of interest discussed is assigning the channel (assigning a hopping sequence) every time the push-to-talk (PTT) switch is pressed. The user keeps that channel for that transmission. When the PTT switch is released, the channel (hopping sequence) is free.

There is an equation for the probability of collisions for FH-FSK. Here is an excerpt from "Digital Transmission Engineering" by John B Anderson page 421

"Error probability based on Collisions. The dominant error sources in FH-SS are ordinarily jamming and other-user multiple access interference, not Gaussian noise. The error calculations is based on signal collisions. After the mix-down by cos wt, the radiometer simply looks for energy lying above the receiver noise floor. If it finds energy in exactly one of the M FSK bands, detection is successful; several interferers may contribute, but since no other band is occupied, the desired sender must have been one of them. If it finds energy in two or more bands, either can be the sender and a detection failure is declared.

If we assume random hopping sequences over L frequencies by K independent interferers who send random data, what is the probability Pf of this failure? A collision of a given interferer I and the desired signal occurs with probability

P[I misses FSK frequency] given [I hits hop channel] times P[I hits hop channel]

this equals [(M-1)/M] times 1/L

For successful transmission, this must fail to happen K independent times, so that

Pf = 1 - (1 - [(M-1)/ML]) raised to the K power

A tight approximation is given by

1 - exp[-(K/L) * [(M-1) / M]]

The collision probability is thus set by the ratio of interferers to hop set size, K/L. This differs from DS-SS multiple access, where error probability could be improved by increasing power, providing K < L -1.

As an example, take a binary FKS system K=5 interferers and hope set size L = 20. Equation yields Pf = 0.119, and the approximation is 0.118. To reduce Pf to 0.01 requires size 249. This performance is not good, but parity check coding improves it rapidly with little expense. The collisions count as erasures, not errors, and parity check decoders correct up to d-1 erasures, where d is the Hamming minimum distance."

In other words,

P[interferer is sending a different tone than you are] given [interferer managed to crash your channel] times P[interferer managed to crash your channel]

He crashed your channel, and he is not doing you the favor of doubling your particular tone, which wouldn't cause an erasure or error. Let's plot some curves to see what this looks like.

$L := 250$ Number of channels available in the uplink.

$K := 85$ Number of users at a maximum with receiver noise temperature of 120K and a spacecraft transmit power of 50W. This is the maximum from the uplink capacity calculations above.

$M := 8$

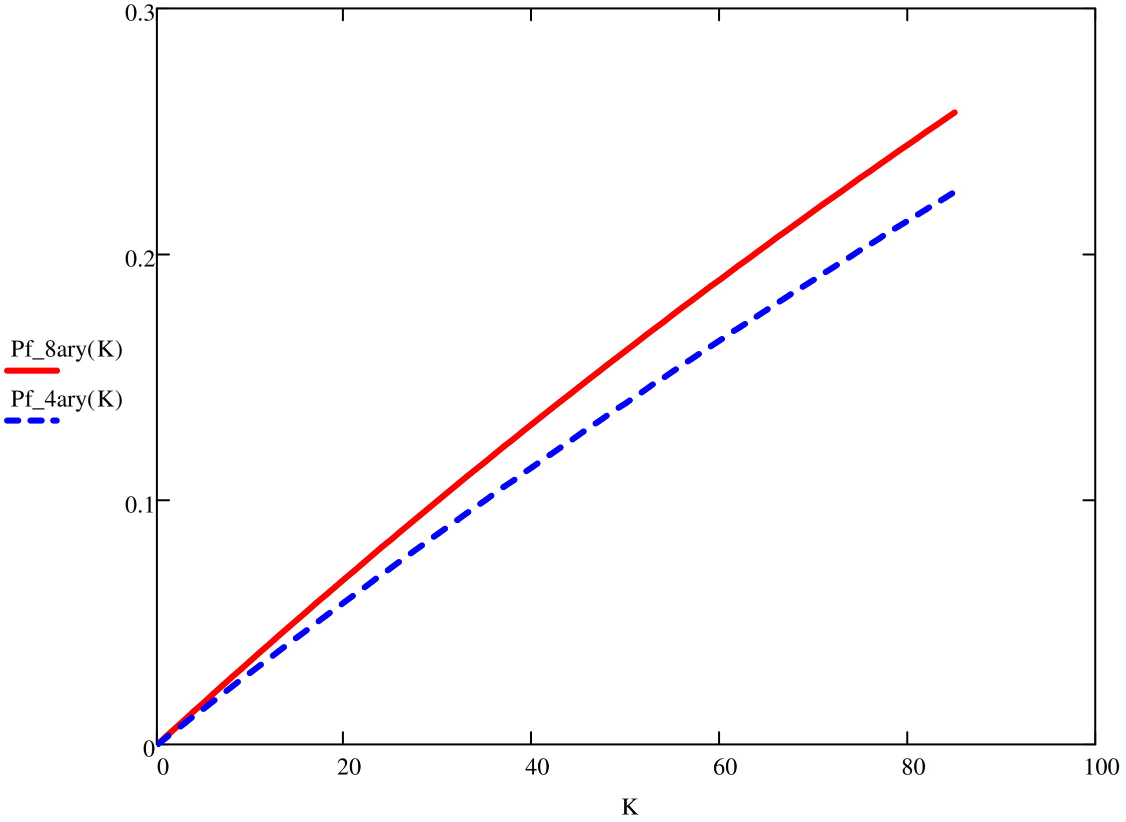
$$Pf\_8ary(K) := 1 - \left[1 - \left[\frac{(M-1)}{M \cdot L}\right]\right]^{K} \qquad Pf\_8ary(K) = 25.771 \times 10^{0} \cdot \%$$

$M := 4$

$$Pf\_4ary(K) := 1 - \left[1 - \left[\frac{(M-1)}{M \cdot L}\right]\right]^{K} \qquad Pf\_4ary(K) = 22.538 \times 10^{0} \cdot \%$$

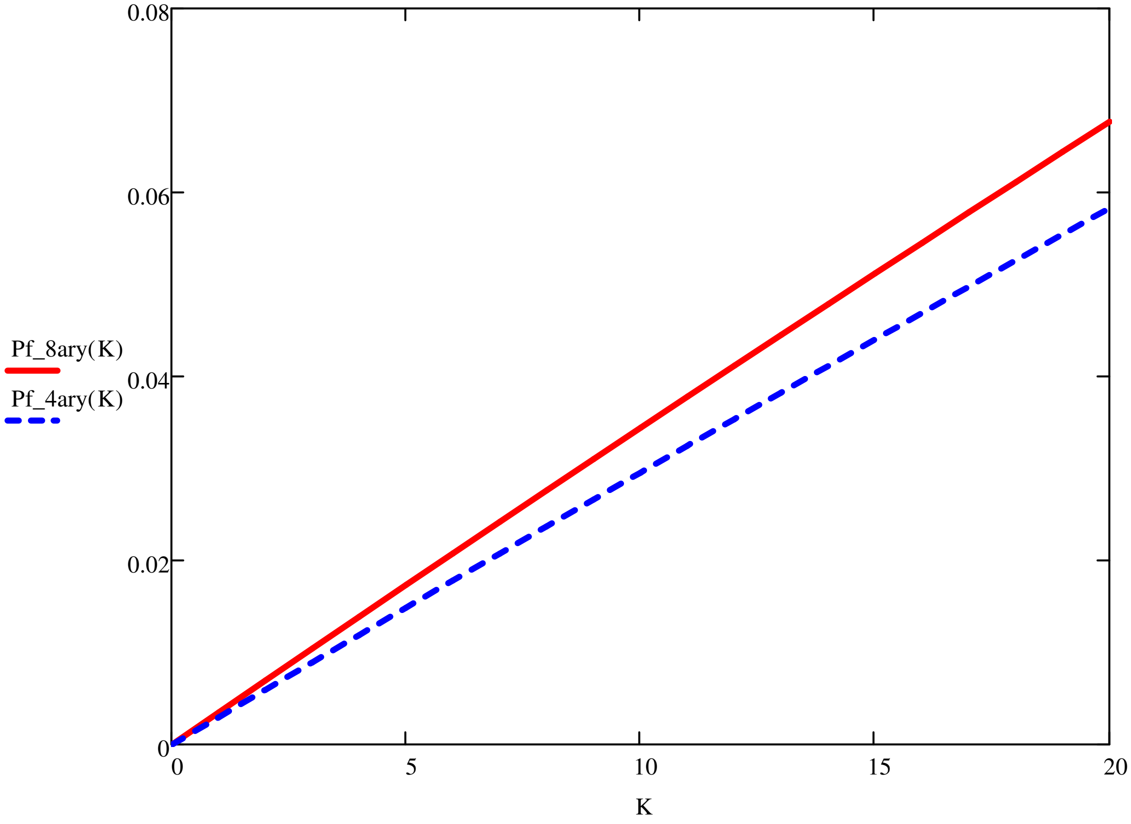
A worst-case calculation would be the probability for collision if all 85 users each attempt to get a channel at once. That probability is 25%. What is it for a more typical operation? Let's plot collision probability vs number of users for 250 channels, for 8-ary FH-FSK. 4-ary FH-FSK is plotted for comparison. The number of users is varied from 0 to 85.

$K := 0 .. 85$



Picking a smaller satellite population, let's examine the lower end of the graph in detail.

$K := 0..20$



Probabilities of collision range from 0.7% for 2 users to 6.8% for 20 users (8-ary FSK).

$\text{Pf\_8ary}(2) = 698.775 \times 10^{-3} \cdot \%$

$\text{Pf\_8ary}(20) = 6.772 \times 10^{0} \cdot \%$

A question is, if collisions are the dominant source of erasures, then what is the upper limit of the error probability that we can correct for with our forward error correcting coding? Since the number of uplink channels is fixed at 250, and since we're considering 8-ary FSK, the other degree of freedom is the number of users.

With 250 channels, and 5 independent users sending random data using 8-ary FSK, the probability of failure due to collision is 1.73%.

Are these numbers too high for amateur radio application? These are erasures, not errors, so the FEC could possibly ride over most of these errors. It's time to try and figure out what the upper bound on uplink errors would be if the erasures due to collision are the major factor in access failure. That will be the next big step for this document.

Another question is that if we increase the number of channels by increasing the number of hopping sequences above 250 then what would would happen to the probability of collision? This means that some of the hopping sequences shared parts of their sequences with others in the system, and shared sequences would have to be sorted out by the spacecraft. This increases the code space, in the sense that hopping sequences are generated by a pseudorandom noise sequencer, which produces a code for that particular channel.

Fixing the number of users at 85 (a theoretical downlink maximum calculated above) the number of channels is varied from 1 to 1000, and the probability of collision is calculated.

$K := 85$

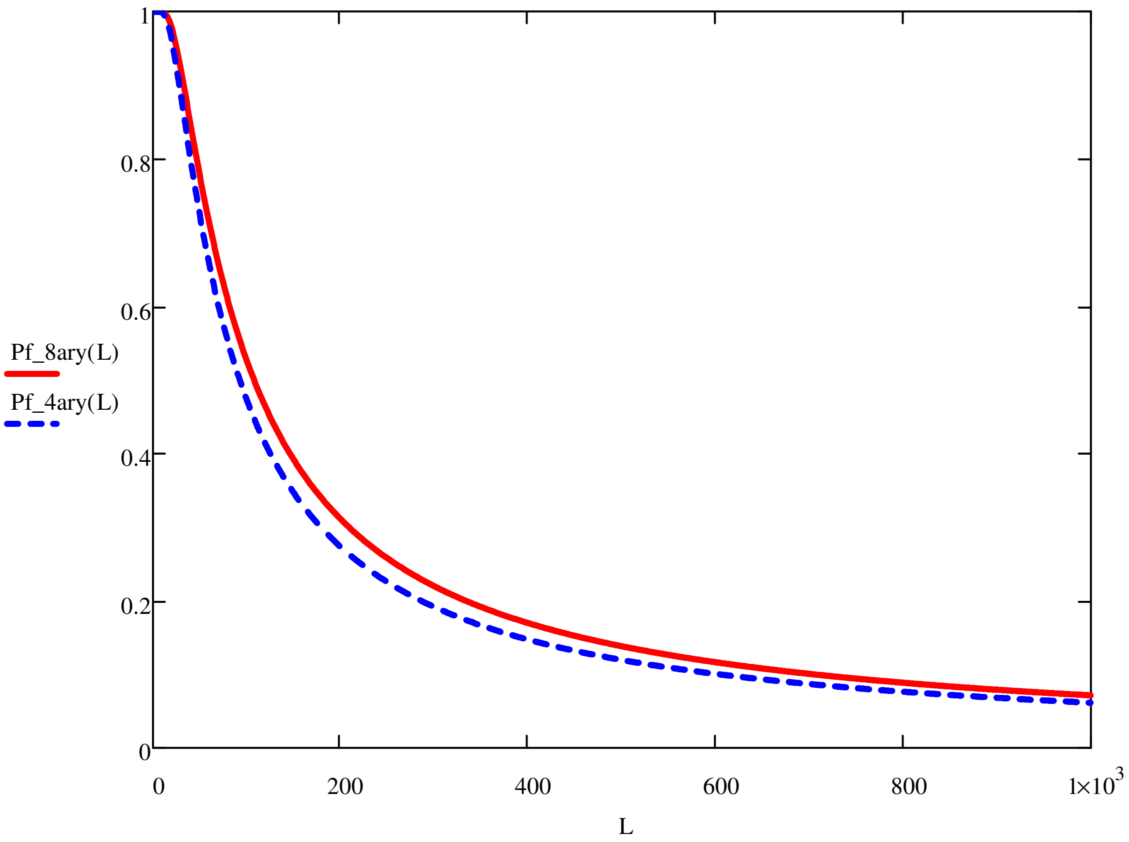
$L := 1 .. 1000$

$M := 8$

$$Pf\_8ary(L) := 1 - \left[1 - \left[\frac{(M-1)}{M \cdot L}\right]\right]^{K}$$

$M := 4$

$$Pf\_4ary(L) := 1 - \left[1 - \left[\frac{(M-1)}{M \cdot L}\right]\right]^{K}$$



This shows the effect of adding new channels to an FH-8ary FSK system with 85 independent users transmitting random data. The probability of collision decreases rapidly and then flattens out.

$L := 1000$

$Pf\_8ary(L) = 7.171 \times 10^{0} \cdot \%$

At 1000 hopping sequences, the probability of collision is 7%. This illustrates what additional channels will do.

Deciding to make channel assignments upon PTT means that collisions (if they prevent successful channel assignment) can erase the entire transmission. A possible improvement is to make channel assignments more frequently. If the channel assignments are made more frequently, then the granularity of the erasure is much smaller. It seems that it would be much more tolerable as a user to lose a symbol than an entire transmission.

We want to make sure that access failures are rare.
When there is an access failure, we want there to be an automatic recovery if possible.
When the automatic recovery fails, we want there to be an indication for the human.

How would we provide an indication for the human? How would a person know if they had failed to access the satellite?

The transmitting station expects to receive its own data in the downlink at some time on the order of 250-280mS later. With that amount of delay, it's confusing to monitor your own actual received signal. Generating a local sidetone provides a no-delay voice monitor, but doesn't have any signal quality information.

Therefore, generate a local sidetone that is modulated by the quality of your own received signal, as recovered from the downlink.

or

Generate a local sidetone that is modulated by the quality of your signal as received by the satellite. This is sent to you as telemetry.

or

A combination of the two.

There is a delay, but a failure could be noticed by the absense of sidetone on the order of low hundreds of milliseconds.

Revision History

version 1.0
mid-May 2008
Presented basic link budget for the downlink

version 2.0
29 May 2008
by W5NYV, KA9Q, KB5MU
Changed document based on the modulation baseline conversation with KA9Q.
Added uplink.

version 3.0
4 June 2008
by W5NYV, KA9Q, KB5MU
Corrected errors in uplink section. Did some housekeeping.

version 3.1
17 June 2008
by W5NYV, KA9Q, KB5MU
Added justification for consideration of FH-FSK from KA9Q.

version 3.2
20 June 2008
by W5NYV, KA9Q, KB5MU
Added classic FH FSK discussion.

version 3.3
22 June 2008
by W5NYV, KA9Q, KB5MU
Added probability of collision and a discussion of desirable system behavior.

version 3.4
22 July 2008
by W5NYV, KA9Q, KB5MU
expanded the document to include terrestrial operation as well as satellite simulation.