Link Budget and Radio Channel Properties

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Note

This is a part of my thesis, titled *On the Use of Micro Satellites as Communication Nodes in an Arctic Sensor Network*, please do not distribute (yet).

1 Link Budget and Link Budget Parameters

A link budget is used to assess and evaluate the quality of communication links, and it expresses the expected signal-to-noise ratio at the receiver. The result of the link budget can be expressed as a required *carrier-to-noise* ratio ($\frac{C}{N}$), the carrier to spectral noise density ($\frac{C}{N_0}$), plus a margin, or as a *sensitivity* value.

The basic link budget equation is:

$$\frac{C}{N_0} = \frac{E_b}{N_0} \cdot R_b = \frac{G_t P_t}{L_0} \cdot \frac{G_r}{T_{sys}} \cdot \frac{1}{k} \cdot \frac{1}{L_a} \tag{1}$$

N_0 is the spectral density of the noise, and E_b is the energy per bit. G_t and P_t are the antenna gain for the transmitting antenna and the transmit power, respectively. This term is often denoted Effective Isotropic Radiated Power (EIRP). G_r is the receiver antenna gain. L_0 is the free space loss defined as $\left(\frac{4\pi d}{\lambda}\right)^2$, with λ as the wavelength and d is the distance between the transmitter and receiver. T_{sys} is the equivalent system noise temperature, k is Boltzman's constant and R_b is the data rate of the system. L_a is the additional losses accounted for, and the individual factors will be identified and discussed in the following.

To fully comprehend the link budget, different parameters and their effects should at least be sized and estimated. Here, ionospheric scintillation, polar cap absorption, Faraday rotation, polarization loss, multipath and dispersion will be considered.

Different effects inflict the signal in different manners, both with respect to fading depth and the duration of the fading period. Short fading, scintillations and fading due to for example shallow multipath, stemming from reflections from the sea surface, can according to [1] be modeled as Additive White Gaussian Noise (AWGN). Common Forward Error-correction Code (FEC) codes can mitigate this fading and increase the margin. However, deeper fading will have a longer duration and cause more loss of data than the codes can handle. To mitigate such effects, signal processing techniques such as equalization, frequency and/or spatial diversity or packet retransmission could be considered. The complexity of the mitigation techniques must be traded against the gain in reliability each method gives.

1.1 Polarization Loss

Due to Faraday rotation, the polarization of a signal will change on its way to or from a satellite. From the International Telecommunications Union (ITU) recommendation ITU-R P.618-12 [2] we find that a 100 MHz and a 500 MHz signal will experience Faraday rotation in the order of 30 and 1.2 rotations respectively. In order to counteract the Faraday rotation, either the node or the satellite (or both) should have a circular polarized antenna. This is typically done for frequencies below 6 GHz [1, Chapter 2.5]. For the link budgets between sensor nodes and satellite(s), it is assumed that the sensor node has a vertical linearly polarized antenna and the satellite has a circular polarized antenna. The cost of this setup is 3 dB polarization loss and it is added to the link budget.

1.2 Dispersion

Different frequencies will experience different propagation delays through the ionosphere. Due to this effect, the signal will experience dispersion. According to ITU-R P.531-12 [3], these effects must be taken into account for wide band systems at VHF and UHF. An example shown in [3] is that a 1 μs signal can experience a differential delay of 0.02 μs, which is 2% of the pulse duration. For a narrowband application, this is of less importance.

1.3 Ionospheric Scintillation

The dynamics of small scale structures in the ionosphere can cause rapid changes in the amplitude and phase of a signal traveling between a satellite and a ground node. These irregular structures are due to local variations of electron density. This in turn causes the refractive index to change, which will influence the signal [1, Chapter 2.3]. The fading due to ionospheric scintillation can vary a lot; from small variations to deep fades that could cause link outages. Also, the properties of this fade vary with the time of day, the time of year, the geographical location and the sun activity.

The scintillation effects typically occur after local ionospheric sunset, meaning that it is a phenomenon that takes place in evenings or at night-time. Typical event durations are from 30 minutes to several hours. When the solar activity is at its maximum in a solar cycle, these effects can be strong and occur every evening [3, Chapter 4.2]. The polar areas are generally less affected than the equatorial zones, but aurora phenomena can cause scintillation at high latitudes [4].

Due to all these inter-connected phenomena, deriving a full statistical model for the ionosphere is nearly impossible, according to Allnut [1, page 119]:

> *"the concept of annual statistics is of dubious merit for ionospheric phenomena."*

The goal here will therefore be to derive a suitable average value for ionospheric scintillations margin to be used in the link budget.

A frequently used parameter to describe ionospheric properties, is the $S4$ index, which characterizes the severity of amplitude scintillation. It is given by Briggs and Parkin [5]:

$$(S4)^2 = \frac{(\langle I^2 \rangle - \langle I \rangle^2)}{\langle I \rangle^2} \tag{2}$$

I is the received signal amplitude and $\langle\ \rangle$ means average [1]. To find an estimate for *peak-to-peak* values, equation (3) is used, where the $S4$-index from equation (2) is used. This is an empirical formula estimated from observations [3]:

$$P_{fluc} = 27.5S4^{1.26} \tag{3}$$

Figure 1 (from [3, Chapter 4.1]), shows one example of VHF and UHF measurements from Sweden in 2003. From this data, it is found that the scintillation indices, for VHF and UHF respectively, are between approximately 0.4 to 1.5 and 0.2 to over 1. This corresponds to *peak-to-peak* values between 3.5 to 27 dB (by using equation (3)). The duration of high scintillation values are several tenths of minutes. This means that the system might experience a signal fade during the whole satellite pass, with loss of communication as the consequence given a large loss.

However, these *peak-to-peak* values do not provide an usable value for the link budget. The scintillations can be described by the Nakagami-distribution [3, 1], and this can be used to derive a margin. This distribution models deviations from an RMS value. The parameter for the Nakagami-distribution, $m = 1/S4$, and its cumulative distribution, shown in Figure 2, show for which percentage of the time the fading is worse than a set level.

Scintillation effects are typically classified into *weak* ($S4 \leq 0.3$), *moderate* ($0.3 < S4 < 0.6$), and *strong* ($S4 \geq 0.6$) regimes. Here, a value for $S4 = 0.5$ is chosen. This is in the moderate regime. If $S4$ is chosen too low, the resulting link budget might be too optimistic and higher outages or less throughput than expected will be experienced. On the other hand, if $S4$ is estimated too high, then the link budget will be too pessimistic and the full potential of the channel will not be exploited. $S4 = 0.5 \Rightarrow m = 4$ is believed to be a reasonable choice.

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The red line in Figure 2 shows the situation when $m = 4$ (the curve for $m = 4$ is lacking in the figure from [6], so the value is interpolated between the lines for $m = 3$ and $m = 5$) and the margin, 7 dB, shall not be exceeded by more than 1%. The blue line shows the case for $m = 4$ and a 10% level and corresponds to 3 dB. These results will be further discussed and concluded in the link budget calculation in Section **??**.

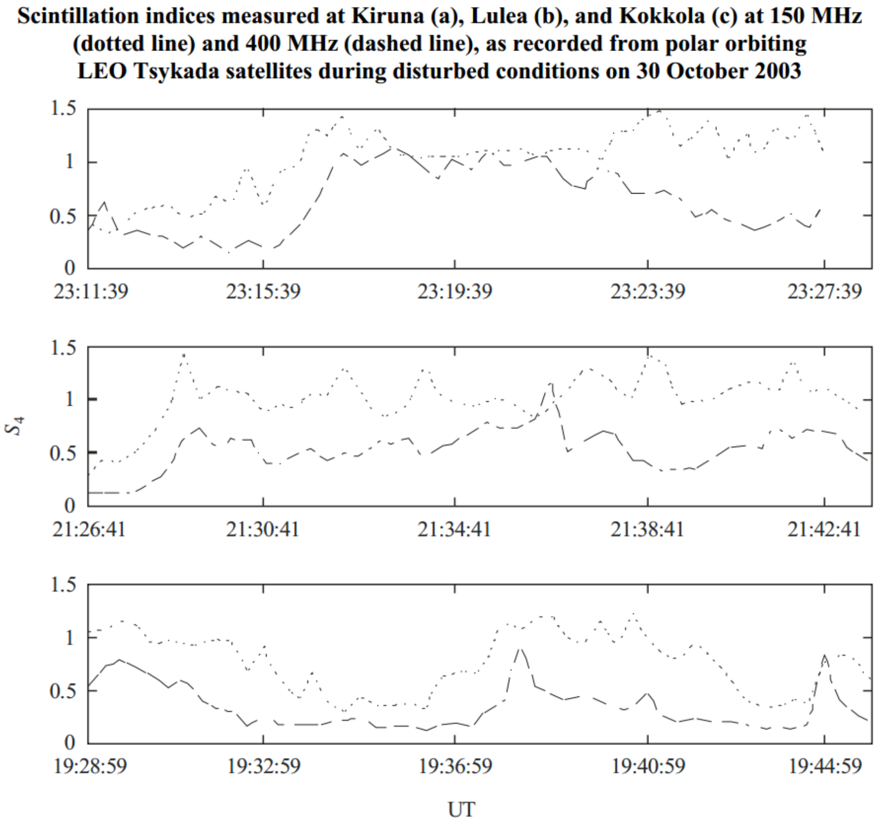

Figure 1: Scintillation indices measured in northern Sweden. From [3, Figure 5].

Figure 2 shows that the distribution is very sensitive. This causes the estimate of the required margin to vary a lot with regards to the choice of $S4$. If we chose $S4 = 0.3$ (weak), $m = 11$. From Figure 2, we then get that an estimate for the fading margin to be between 3 and 4 dB for both 99% and 90% levels. On the other hand, if $S4 = 1$ (strong), $m = 1$, then the required margin will be between 10 to 20 dB. For even higher $S4$, the required margin will have to be huge.

It should be noted that uncertainties like this are further arguments to make use of Adaptive Coding and Modulation (ACM) and Variable Coding and Modulation (VCM) techniques to adapt the use of the channel to its real true-time properties (see Section 5). Implementation of these concepts are suggested for future work.

STK can implement the ITU-models for atmosphere, troposphere, rain and ionosphere. For a simple setup with a satellite in a 500 km 98° polar orbit with an UHF transmitter and a ground station receiver on Svalbard, it is found that the average level for the ionospheric scintillations is 7.3 dB. The fading value varies from 26 dB to close to 0 dB. This is plotted in Figure **??** on page **??**. For S-band STK reports less than 1 dB estimated ionospheric loss.

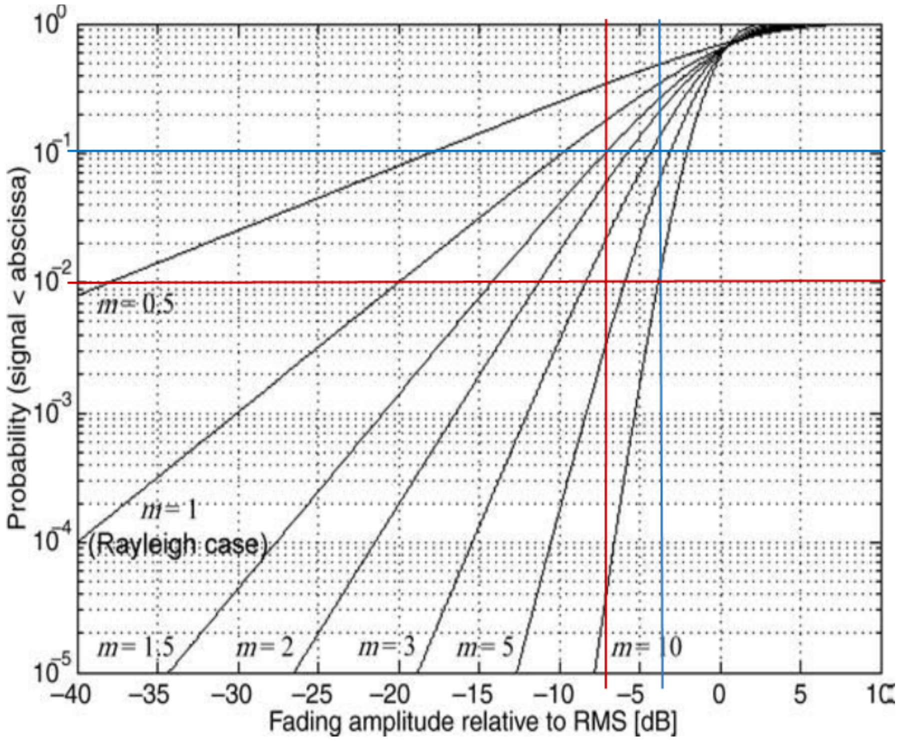

Figure 2: Nakagami-m distribution for ionospheric scintillation. Adapted from [6].

1.4 Polar Cap and Auroral Absorption

Polar cap absorption and auroral absorption are rare events. Auroral absorption can last for hours. For elevation angles greater than 20° the signal loss at VHF is expected to be less than 1 dB for most of the time as stated in ITU Recommendation 531 [3, Table 2].

Polar cap absorption is a very rare event, usually occurring 10-12 times a year during sunspot maxima only. However, the signal loss can be significant, and the duration can be on the order of days [3, Chapter 5.2].

1.5 Atmospheric Effects

Other atmospheric effects such as rain fading are not present at the frequencies considered here; namely VHF/UHF and S-Band. In addition, a low amount of precipitation is expected in the Arctic areas.

When modeling with STK, it is found that losses due to atmospheric, rain, and cloud conditions are all less than 0.1 dB. They are therefore chosen to be neglected in the link budget. For very low elevation angles, tropospheric scintillation is modeled to be 40 dB loss, while for elevation angles above $> 3°$, this loss component is 0 dB. This effect will also be neglected in the link budget as we assume operating at elevation angles above 3°. These effects are similar for UHF and S-Band cases.

1.6 Other Effects

In addition to the losses mentioned above, the system will be prone to signal degradation due to several other factors. Examples are antenna pointing errors due to misbehaving Attitude Determination and Control System (ADCS). Ocean wave movements can drown or shadow the node antenna. Icing of antennas can occur as well as multipath fading effects due to reflections from ocean or ice surface. The value of these effects is hard to estimate. A large system margin could account for some of these effects. Link losses can in some cases be expected, especially due to antenna icing and shadowing. In addition, a large (conservative) system margin will in most cases give conservative results indicating lower data throughput than what is actually possible. Again, VCM and ACM should be employed in order to make the best possible use of the link.

Since both polar cap absorption and the periods of high scintillation values are tied to periodic ionosphere activity due to solar activity, we can argue that the link budget should not account for the peak values of these two parameters. At rare and extreme events, ionospheric scintillation can cause losses greater than the system fade margin. For a non-critical communications system, it can be accepted that we lose communication during strong/extreme events. However, some losses should be taken into account in the link budget.

2 Receiver Noise Calculations

Several physical phenomena lead to noise and disturbance of a signal. Traveling through the ionosphere and atmosphere, rain and so on will also increase the noise level of a

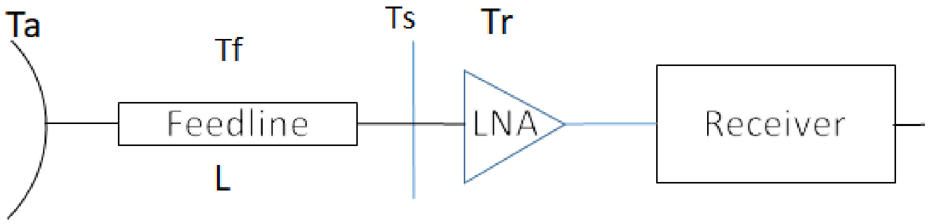

Figure 3: Noise calculations for a receiver.

signal. These phenomena contribute to the ambient environment and temperature the antenna observes. In addition, the components in a receiver contribute to the noise level. Also, noise from the surroundings, it being as interference or "general" increased RF noise levels should be accounted for. However, for sensor systems placed in solitude in the desolate Arctic, this contribution is small.

An estimate of the resulting system noise can be calculated by using a model shown in Figure 3. In this case, we reference the system noise at the input of the Low-Noise Amplifier (LNA), after the loss from the feed-line between the antenna and the LNA.

From this, we can write the corresponding system noise temperature T_s as:

$$T_s = \frac{T_a}{L} + T_0(1 - \frac{1}{L}) + T_r, \tag{4}$$

where T_a is the antenna temperature, $T_0 = 290K$ is the ambient temperature denoted T_f in Figure 3, L is the loss (linear) in the feed-line and T_r is the equivalent noise of the receiver. The noise of the receiver can in most cases be approximated to the noise temperature of the LNA [7, Chapter 5.5.2.5], as long as the gain of the LNA is high.

2.1 Satellite Antenna Temperature - Uplink

The satellite antenna will, depending on the antenna pattern, see a portion of the Earth as well as the empty space. The true antenna temperature is an integral over the brightness temperature the antenna diagram "sees". For a low-gain antenna, the Earth will contribute only a fraction of this temperature. However, as a conservative estimation $T_a = 290$ K can be used [7, Chapter 5.5.3.1].

2.2 Ground Antenna Temperature - Downlink

For a receiving station on Earth, the observed antenna temperature will be lower, as the antenna sees the cold space, in addition to the noise contribution by the atmosphere. If the antenna has a broad lobe and a low elevation angle, the ground will also contribute. From [7, Chapter 5.5.3.2.1] the antenna temperature can be estimated to be as low as 10 - 50 K for clear sky conditions. Referring to [8], galactic noise must also be taken into account. Hence an estimate of 250 K for UHF and 100 K for S-Band will be used in the link budget calculations in Section ??.

Figure 4 shows some of the contributions to the antenna noise temperature. It is for example noise from the ground, the sky and from rain. Depending on the amount of rain clouds, all contribution from the sky might be attenuated through the rain clouds. Further, the noise temperature due to the rain clouds will then be greater. As mentioned, the contribution from for example rain will be small in our case; both due to very little precipitation and due to that UHF frequencies are not affected by rain at any great degree.

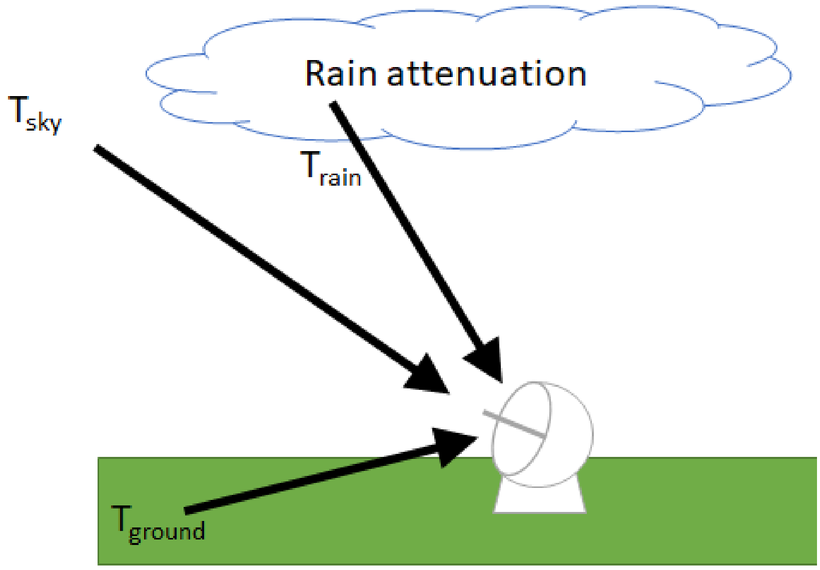

Figure 4: General representation of antenna noise and temperature. Several physical processes can contribute to the antenna noise. Some are shown in this figure.

3 Channel Coding

By introducing redundant bits in the data transmitted over the RF channel, we can increase the probability of successful decoding, for a given signal to noise ratio. The cost of this is that the introduced redundant bits reduce the usable bit rate. Various existing Forward Error-correction Code (FEC) schemes can be used. The codes have different properties; both when it comes to code strength and complexity in decoding [7, Chapter 4.3]. Figure 5 shows typical code gains for a selection of code rates, based on Viterbi decoding of a convolution code. The figure is based on Table 4.5 in [7, Chapter 4.3.2].

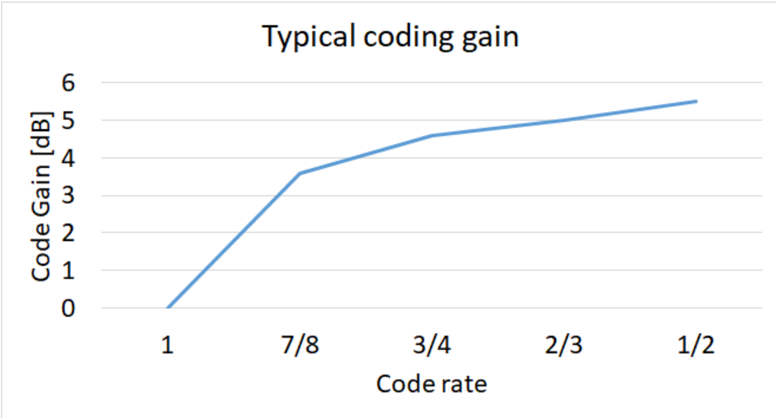

Figure 5: Typical coding gain. Adapted from Table 4.5 in [7, Chapter 4.3.2].

4 Modulation

For low-power operations, a simple, but spectral effective, modulation should be selected. Figure 6 shows Bit Error Rate (BER)-curves for a selection of digital modulations. As observed, the modulations BPSK and QPSK have the lowest E_b/N_0-requirement for a given BER. As QPSK transmits two bits per symbol, giving twice the data rate compared to BPSK, this modulation is chosen as baseline for link budget calculations.

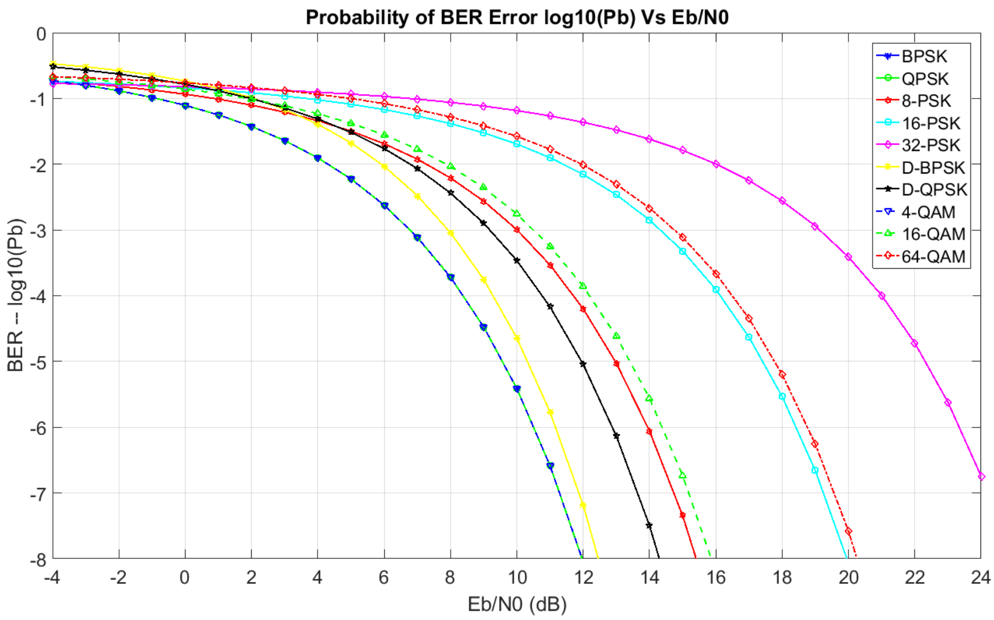

Figure 6: Curves for Bit-Error-Rates for a selection of digital modulations.

5 Adaptive Links

The previous sections have shown that since the environment and the radio channel are changing over time, the use of adaptive links should be considered. This means that if the link budget for a given link condition, with respect to range, weather, and ionospheric conditions, has room for extra capacity compared to other link conditions, this improvement could be cashed out in different ways. For example:

- Power saving – less power is needed to maintain a link, still supporting the same bit rate
- Higher throughput – same amount of power used, but a higher rate and/or higher order modulation can be used when the link margin supports it

The challenging part can be how to define the signaling channel and the fall-back modes, as the contact time during each pass is quite short. The link yield is depending upon the transmit power, the distance between the transmitter and receiver and the channel properties.

5.1 Causes of Variability

The following phenomena may cause high variability in link quality, and could therefore be justifications on why adaptive links are sought for.

Distance The distance between the transmitter and receiver can easily be calculated by knowing the satellite orbit. The maximum distance for a given pass can be calculated in advance. As an example, the distance can vary between around 3000 km (horizon) and 600 km (zenith). This corresponds to around 14 dB ($20log(\frac{3000}{600})$) change in received power level. An example of this is shown in Figure 7. Here, the usable dynamic range is 10 dB. The steep cut-off is due to implementation of ITU-models for ionospheric and tropospheric scintillation which STK estimates to be severe for low elevation angles.

Atmospheric and ionospheric conditions VHF and UHF frequencies are not very prone to effects of atmospheric variations, such as attenuation due to rain or water vapor. Also, the Arctic is mainly considered a desert. However, for south-north-moving satellites, the link might go through parts of the atmosphere that contain more vapor. In addition, ionospheric scintillations can occur as shown in Section 1.3. Even more, the link will also be affected by solar energy bursts. These are rare events that can be monitored and a forecast can be issued. If such effects occur, they can cause losses that are larger than the system fade margin even if very low bit rates are used. Outages due to this will be rare occurrences and should be tolerated for a system as discussed here.

Local conditions The link can be affected by fading due to several local conditions, such as icing and wave movements if the node is floating. Reflections due to waves and local surroundings can also lead to a changing multipath environment. The value of this

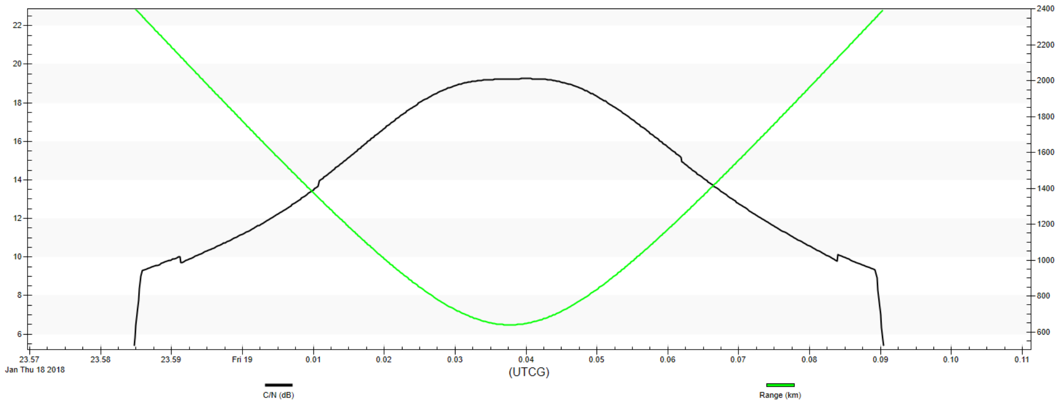

Figure 7: Example of estimation of received C/N during a near overhead pass. The black line is the C/N-value, the green is distance from ground station to satellite. The left Y-axis is in dB, the right Y-axis is km and the X-time unit is hours.

fading can be several dB. According to [9, Chapter 6.3], multipath can be severe for any elevation angle in a low-frequency system using low gain antennas. The impact of different parameters such as elevation angle and sea state is discussed in [1].

5.2 Adaptive Coding and Modulation

Since the received power level varies during the pass due to for example varying distance, the link properties are quite different in the start and end of a pass, compared to during the middle section of a pass (especially valid for overhead passes).

In order to make the most use of channel capacity, Adaptive Coding and Modulation (ACM) or Variable Coding and Modulation (VCM) can be employed. This can be a change of the code rate; so that packets transmitted in the start of a pass can have a simpler modulation or have a stronger code than packets transmitted when the received power is higher. This dynamics can be as high as 20 dB, according to [10]. If we slice the curve in Figure 7 for every 2 dB, we can have 5 different Coding and Modulation Scheme (CMS) if desired.

The extra implementation cost due to increased complexity on adaptive links must be traded against the chance of achieving more data throughput in some passes.

5.2.1 Variable Coding and Modulation Schemes

In order to make ACM work, the receiving node (satellite, sensor node or gateway) must constantly inform the transmitter of how the signal is received. This can be implemented in several ways, one way is to note the output from the FEC process and derive an estimate for the BER. If few packets are received, the transmitter should be requested to reduce the data rate or change to a stronger code. A time-out should be in place both in transmitter and receiver in order to fall back to a basic CMS in case of failure of a more "advanced" CMS.

Figure 8 shows how the loop controlling the ACM-functionality can behave. In the satellite there will be a function estimating the received link quality which in turn instructs the sensor node to use a specific CMS suitable for the present radio channel. An implementation for an SDR is proposed in [10].

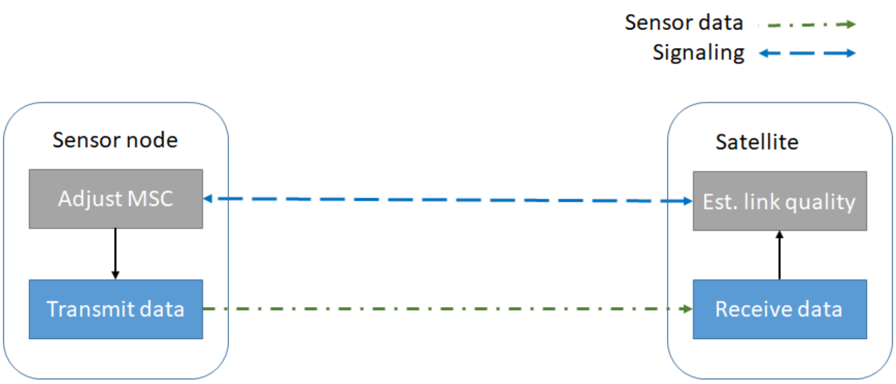

Figure 8: Model of ACM control loop.

5.2.2 Rate-less Codes - Hybrid ARQ

A method to transmit as much usable data as possible, which also enables the ability to handle varying reception properties is to employ rate-less codes. A data transfer between the sensor node and the satellite can start with a coding scheme where data with just a little code is transmitted. However, the transmitter still makes a very long code word. If the packet is received correctly (determined by a CRC-code), then an ACK can be issued. However, if the decoding of the packet fails, then an ARQ is issued. The source will then issue an additional segment of the code word, that the receiver will add to the first received packet. This process may continue until the packet is successfully decoded, or until a timeout is reached. This method is also called Hybrid ARQ [11].

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Acronyms

ACK ACKnowlegde. 12

ACM Adaptive Coding and Modulation. 4, 6, 11, 12

ADCS Attitude Determination and Control System. 6

ARQ Automatic Repeat reQuest. 12

AWGN Additive White Gaussian Noise. 2

BER Bit Error Rate. 9, 11

CMS Coding and Modulation Scheme. 11, 12

EIRP Effective Isotropic Radiated Power. 1

FEC Forward Error-correction Code. 2, 8, 11

ITU International Telecommunications Union. 2

LNA Low-Noise Amplifier. 7

SDR Software Defined Radio. 12

STK Systems Toolkit. 4, 6, 10

VCM Variable Coding and Modulation. 4, 6, 11

List of Definitions

RMS Root-mean-square, a way of describe an average signal level. 3

S-Band A radio communication band that spans the 2 - 4 GHz frequency range (IEEE definition). 6, 8

sensitivity The sensitivity (level) of a receiver can be described as the signal needed at the receivers input in order to get the required signal-to-noise ration on the output for a given bit-error-rate and modulation [12]. 1

UHF Ultra High Frequency. A radio communication band that spans 300 - 3000 MHz (ITU definition). Usually used to denote frequencies from 300 - 1000 MHz (IEEE definition). 2–4, 6, 8, 10

VHF Very High Frequency. A radio communication band that spans 30 - 300 MHz (ITU and IEEE definition). 2, 3, 6, 10