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TOWARDS THE NEXT GENERATION OF NANOSATELLITE COMMUNICATION SYSTEMS

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Abstract

The communication systems currently used on nanosatellites are usually well-proven commercial-off-the-shelf units with data rates up to 9.6 kbps. A careful analysis shows that by using advancements in microelectronics, a higher communication performance can be achieved, even within the power and mass limitations of a nanosatellite.

This paper presents a new approach to maximize the performance of nanosatellite communication systems by taking a systems engineer's perspective and by regarding the entire satellite instead of the communication system only. It is found that efficiency can be gained by also including the electrical power system in the design. The parameters that influence the performance of the communication system are identified. It is shown how these parameters can be tuned such that the limited resources on a nanosatellite are used most effectively.

The results are used in designing the communication system of Delfi-n3Xt, the next nanosatellite mission of Delft University of Technology. The results presented in the paper can be used as a guideline to designing a nanosatellite of the next generation.

1 Introduction

In the past few years around 40 university nanosatellites have been built (CalPoly, 2008). Some of them have failed, either because of a failure of the rocket, the Dnepr launch in June 2006 being the most dramatic one with 14 nanosatellites not reaching orbit, or because some satellite subsystem has failed in orbit. However, there have been a number of successes as well. Delfi-C^3, the first nanosatellite built by Delft University of Technology and launched at 28 April 2008, is one of the more successful missions. Nanosatellites will continue to be built, since nanosatellites have a number of advantages over large satellites: low cost, short development time, in-orbit testing of new technologies, and, of course, educational goals.

The first generation of nanosatellites is now in orbit, and the second generation is being developed. This is also the case at Delft University of Technology. Delfi-C^3 performs according to specifications, and the follow-up mission, named Delfi-n3Xt, is nearing the end of the preliminary design phase. Delfi-n3Xt can, however, not be "yet another nanosatellite", but it has to be better than previous satellites. The question is how to increase the performance of nanosatellites.

This paper discusses the communication system of nanosatellites. It identifies ways to improve it, and it shows why these improvements should be made. In the first section the analysis of system-level parameters is presented. The second section focuses on the implementation of the communications system. Finally it is shown how the results of this analysis are used in the design of the communication system of Delfi-n3Xt. Only digital communication is taken into account, since digital data is formatted and manipulated more easily than analog data, and any new small satellite mission will use a digital format to convey information from the satellite to the ground.

2 System level parameters

In order to improve the communication system, it must be known what exactly needs to be improved, and where possibilities are where the system can be improved. To start this analysis, it is good to review what exactly the communication system of a satellite needs to do: to convey a quantity of information from A to B within a certain time. This time varies depending on the type of the data. Telecommands, for instance, need to be delivered right away, whereas payload data can also be transmitted once per day. In the following discussion the satellite downlink is considered, since that is usually the direction of the largest data flow and a transmitter consumes more power than a receiver, but the equations can be used for the uplink in a straightforward way.

2.1 Ground segment

The daily data volume that can be conveyed from satellite to the ground is determined by a number of factors:

- effective data rate,
- ground station coverage,
- pass time.

The effective data rate R_{eff} is the useful data volume divided by the communication time, which differs from the raw data rate R due to protocol overhead and coding.

With the ground station coverage c, the average pass time T_p in seconds per pass, the average number of passes per day n, the daily data volume D is related to these parameters by:

$$D = R_{\text{eff}} c n T_p. \tag{1}$$

It is assumed that the coverage of ground stations does not overlap, and otherwise this can be corrected for by taking a longer pass time. The pass time for a single ground station will vary due to different elevation angles, but instead an average pass time over one unit of time can be used (e.g. one day). The equation can be made more complex by including these differences, but for the sake of the argument this simple equation suffices.

The equation can also be used for including radio amateur ground stations worldwide. The ground station coverage for the radio amateur network can be calculated by taking values from the Delfi-C^3 mission as an example, with an average pass time $T_p = 11$ min, $n = 5.7$ passes per day and the effective data rate $R_{\text{eff}} = 930$ bps (the overhead from AX.25 is nearly 30%). At 14 July 2008, 78 days after launch, a total of 370,000 frames (1 frame has an average size of 930 bits) had been received by the ground station in Delft as well as by radio amateurs worldwide. The ground station coverage for one day can then be calculated to be

$$\begin{aligned} c &= \frac{D_t/P}{R_{\text{eff}} n T_p} = \frac{370,000 \cdot 930/78}{930 \cdot 5.7 \cdot 11 \cdot 60} \\ &= 1.27 \text{ ground stations.} \end{aligned} \tag{2}$$

In the equation above, D_t is the total data volume and P is the mission duration in days. Subtracting the ground station in Delft (which counts as 1) from this value, the size of the radio amateur network is 0.27 ground station on average (with 5.7 passes per day). The share of the radio amateur network in downlink time is then equal to $\frac{0.27}{1.27} = 21\%$. Since this is still a crude estimate, data from more missions is needed in order to be able to provide a range for the value of c. Furthermore, c will vary as the mission progresses, and it also depends on the popularity of the satellite.

T_p and n are fixed when the orbit is fixed, and the daily data volume D follows from the mission requirements. The design parameter is then the product of the effective data rate and the ground station coverage, $R_{\text{eff}} c$. From that it can be derived that if data can be buffered, a higher data rate would decrease the required size of the ground segment. Therefore, the design of the communication system starts with the following steps:

1. Fix the orbit geometry (T_p, n and slant range known).
2. Determine the ground segment (c).
3. Determine the daily data volume D.
4. Determine the required effective data rate R_{eff}.

A note to item 3 is that, for example, critical housekeeping data such as temperatures, battery voltages and received commands should be available right away instead of being downlinked only once per day. This information will therefore more likely be transmitted using a continuous, low data rate link.

2.2 Data rate

A communications link is usually modeled as a noisy channel. The signal enters the channel and exits at the other end with noise added to the signal. The channel has certain capacity for conveying information signals reliably, i.e. it has a maximum data rate. A theoretical relation between signal properties and channel capacity is given by the well-known Shannon theorem (Shannon, 1949):

$$C < B \log_2 \left(1 + \frac{S}{N}\right), \tag{3}$$

where C is the channel capacity (for digital communication the unit is bits per second), B is the bandwidth capacity of the channel in Hz, S is the signal power and N is the noise power. The Shannon theorem cannot be used directly for calculating the required signal-to-noise ratio, because it assumes that a “perfect” modulation scheme is used that uses infinitely long symbols. Efforts are underway to approach the perfect modulation scheme (Viterbi, 1996), but for current practical modulation techniques the actual signal-to-noise ratio required is still a few decibels higher than what follows from Equation 3.

Shannon’s theorem can, however, be used to get insight into what the parameters are that determine the capacity of a link to transfer information from A to B. It is clear from the equation that there are two separate parameters that can be varied: the bandwidth capacity of the channel and the signal-to-noise ratio. It is observed that varying either parameter does not have the same effect. Consider a channel with $B = 3$ kHz and SNR $= 10$, then theoretically $C = 10$ kbps. Doubling the bandwidth ($B = 6$ kHz) doubles the channel capacity ($C = 20$ kbps), but doubling the signal-to-noise ratio to 20 only adds 3 kbps ($C = 13$ kbps). This effect is illustrated in Figure 1.

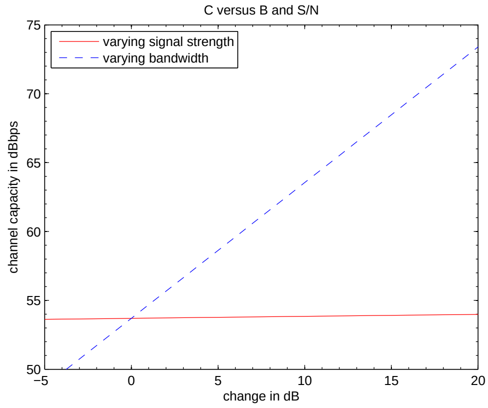

Figure 1: Effect of varying the parameters in the Shannon equation. The nominal case (based on Delfi-C^3) is $B_0 = 2400$ Hz, $P = 250$ mW and the total loss $L = -135$ dB. Note that the scale is double logarithmic.

2.2.1 Bandwidth

Increasing the bandwidth B of the signal can be done in three ways:

- choosing a modulation scheme such that it produces a signal with a wide spectrum;
- coding: adding redundant information and using this to correct errors in the message;
- spread spectrum techniques that spreads the energy over a larger part of the spectrum by modulating the signal with a high speed code.

For successful demodulation of a signal a certain minimum energy E_b/N_0 is required in order to achieve a certain bit error ratio (BER). The bit error ratio is the number of wrong bits in a message of a certain length, usually taken to be 10^{-5} (Larson and Wertz, 2006). With coding the raw data rate is increased by adding redundant bits of information to the signal, but the effective data rate does not necessarily increase. The higher data rate causes the BER to be higher, but after a number of errors have been corrected using the extra information, the resulting message has a lower BER, and therefore a lower signal-to-noise ratio is required for successful demodulation. The difference between the E_b/N_0 corresponding to this signal and the BER of the signal without coding is the coding gain. Both forward error correction and bandwidth spreading techniques have the effect that for the same data rate the signal-to-noise ratio required at the receiver is reduced, so that less transmitter power needs to be used.

One could be tempted to always prefer increasing the bandwidth over increasing the signal-to-noise ration when the system is neither bandwidth-limited nor power-limited. This is only true up to a certain point. The reason is that with increasing bandwidth, also the noise increases, since $N = N_0 B$, with N_0 the noise power spectral density. N_0 is related to the system noise temperature T_s by Boltzmann's constant k: $N_0 = kT_s$. Substituting $N = N_0 B$ in Equation 3 gives

$$C < B \log_2 \left(1 + \frac{P}{N_0 B}\right). \qquad (4)$$

When the bandwidth is increased to the limit $B \to \infty$ the above relation can be approximated by (Proakis and Salehi, 2008):

$$\lim_{B\to\infty} C = \frac{1}{\ln 2} \frac{P}{N_0}, \qquad (5)$$

which means that even with an infinite channel bandwidth a certain signal power is required for reliable communications. This is the Shannon limit, and it holds for any modulation scheme. As can be seen in Figure 1, however, this limit is not important for the bandwidths under consideration, with the other parameters taken to be reasonably normal values for nanosatellites.

2.2.2 Signal-to-noise ratio

Increasing the signal-to-noise ratio S/N can be done by:

- increasing the RF power output of the transmitter power amplifier;
- increasing antenna gain;
- reducing path loss by choosing a lower frequency;
- reducing losses occurring in the system;
- decreasing the system temperature to reduce noise.

While the options for increasing the antenna gain on the spacecraft are limited on nanosatellites, it also entails another disadvantage, which is that in general with increasing antenna gain, the half-power beamwidth of the main lobe decreases. This leads to stricter pointing requirements of both spacecraft and ground station.

2.2.3 Conclusion

It is concluded that increasing the bandwidth of the signal is more effective than increasing the signal-to-noise ratio. If it is assumed that the costs for increasing either parameter (e.g. in terms of engineering effort, available power or money) are comparable then it follows that increasing the bandwidth is better than increasing the signal-to-noise ratio. This is, of course, provided that the extra bandwidth is available. For small satellites this is determined by the bandwidth slots that are assigned to the satellite, either by buying a commercial license or by using the radio amateur bands. The advantage of increasing bandwidth is also recognized in consumer electronics, where bandwidths become wider as well to reduce the required power.

2.3 Burst downlink versus continuous downlink

When the data rate R_{eff} that can be achieved is high enough, there is a choice to be made between using a burst downlink (sending data down in high-speed data bursts and not transmitting for the rest of the time), and a continuous downlink. Mathematically this means choosing a value for c in Equation 1. A higher value means using a worldwide ground station network and a low value of c means that only a small number of ground stations is contacted, with time in between during which the transmitter is off. In this section these two options are compared.

A number of simple equations relate the quantities that determine the performance of the system. Using Equation 1 and the total energy required $E = P_{\text{TX}} T_a$ the energy per bit can be written as

$$\frac{E}{D} = \frac{P_{\text{TX}} T_a}{R_{\text{eff}} n c T_p} \quad \text{[J/bit]}. \qquad (6)$$

Here T_a is the time that the link is active. For a continuous link this is equal to the time during which the data volume D is collected and therefore $T_a \gg cnT_p$. For a burst downlink where $T_a \approx cnT_p$, the equation above reduces to

$$\frac{E}{D} = \frac{P_{\mathrm{TX}}}{R_{\mathrm{eff}}} \quad [\mathrm{J/bit}], \tag{7}$$

from which it follows that when the transmitter power stays the same, a higher bit rate leads to a higher efficiency in terms of energy required to transmit one bit of data.

Another interesting quantity is the continuous power P_c:

$$P_c = \eta P_{\mathrm{TX}}, \tag{8}$$

where $\eta = ncT_p/T_a$ is the duty cycle. This applies when using a battery to store the energy required for transmission. This energy can be gathered during the entire orbit, and be released during a transmission burst. The same holds for data: for a burst downlink the data gathered needs to be stored on board somewhere, and read out during the pass. Note that the power values are RF power values. The actual power consumption will be higher still due to limited efficiency of the power amplifier and because the electronic circuit on the transmitter requires power as well when switched on.

The equations are trivial, but nevertheless the results are noteworthy. They show that transmitting the same amount of data in short high-data rate bursts is more efficient than transmitting the same amount of data continuously using a low data rate link. This shows itself in both the energy required per bit as well as the continuous power necessary for the link.

Some figures are listed in Table 1 to illustrate this. The continuous downlink uses BPSK modulation. The burst downlink works by employing spread spectrum techniques to widen the bandwidth. To facilitate a proper comparison, the noise temperature is taken to be 1000 K for both systems, and the difference between transmitted and received power due to antenna gains and losses equal to −135 dB. In practice these values will differ somewhat between the links. The difference in achievable data rate can be explained entirely by Shannon's theorem: using more bandwidth significantly increases the channel capacity. The difference in continuous power is due to the difference between burst downlink and continuous downlink.

Operational aspects that need to be taken into account as well are:

Table 1: Comparison between continuous and burst downlink.

	Continuous	Burst	
P_{TX}	250	250	mW
R	9.6	250	kbps
E	21.6	0.225	kJ
D	32	116	MBit
E/D	676	2	μJ
η	100	1	%
P_c	250	2.6	mW

- During a continuous downlink a lot of data is lost since there is no global coverage, in particular when the satellite passes over oceans.
- Disturbances that occur during a burst transmission have a higher impact in terms of lost data, due to the higher data rate.

Both problems can be solved by requesting retransmission of data, but then data storage is required. The first problem can also be solved by increasing the ground station coverage, but this is usually unfeasible for small satellites, since they rely on university ground stations and radio amateurs and do not have a dedicated network. Proper selection of coding schemes, for example Reed-Solomon codes, can be used to correct for transmission errors that occur in bursts.

3 Implementation

In the previous section some system level parameters were discussed that define the performance of the radio on system level. In this section the focus is put on the implementation of the communication subsystem. The communication system is split up into parts which are discussed individually.

3.1 Transmitter baseband

Figure 2 shows a breakdown of a typical transmitter. On the left a data stream enters the baseband part of the communication system. This data stream can either be a continuous data stream, or data packets that arrive in bits and pieces. The data can be buffered or fed to the protocol handler directly. Buffering is necessary for example in the case that data is delivered

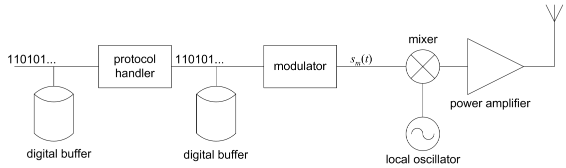

Figure 2: Breakdown of a typical transmitter. The data buffers could be omitted if the bit stream is downlinked directly.

at low data rate and is downlinked in one burst with a data rate that is much higher. The data can also be buffered after the protocol handler has processed the data. This makes the system even more flexible, and when burst transmission is used it would enable the use of a microprocessor that is much slower.

The protocol handler converts the data received from the stream into data frames that can be transmitted. The protocol handler's tasks are:

- optionally compress the data;
- fragment the data stream into separate data blocks that are of the right size (a fixed size can be required by the protocol or the coding scheme);
- optionally compute error correction codes that are sent along with the data to facilitate error correction at the receiver end;
- append protocol fields, for example addressing information;
- append synchronization bytes, which may be required for receiving the signal.

The data stream produced by the protocol handler is a digital data stream that is ready for transmission. The next step is to modulate this data stream onto a carrier signal. There are a number of modulation schemes. Which modulation scheme is used depends on requirements on power, spectrum usage, mass, volume and implementation complexity. All of these are important for nanosatellites, since mass, volume and power are limited. The implementation cannot be too complex, since the system needs to be reliable and the time needed to develop it must also be within the time constraints of the project.

On a small satellite, these tasks are usually performed by a single microcontroller. The microcontroller usually communicates with the command and data handling subsystem via the I^2C or CAN bus protocol. It receives the data in blocks, optionally buffers the data, processes the data, optionally buffers the data after processing, and sends the data to the modulator. The microcontroller is sized on the amount of work it has to perform within a certain time. Data compression, forward error correction and protocol handling all increase the amount of work to be done and therefore the power consumption of the microcontroller or processing time. The advantages that the extra tasks bring about should be traded against the required processing power.

Estimating the required processing power and finding the right microcontroller is not an easy task. It depends on the following factors:

- clock speed at which the microcontroller is used;
- work load for the microcontroller;
- architecture, brand and type of microcontroller;
- compiler efficiency; and
- programmer skill.

Due to rapid advancements in microcontroller and technology and the application dependency it is hard to provide estimates of power consumption. Usually an estimate can be given based on past experience, but more accurate information will only be available when the microcontroller has been selected. This is to be done by experts, and the task of the systems engineer is merely to list all the requirements that the microcontroller should meet.

3.2 Modulation schemes

The protocol handler produces a digital stream that is ready for transmission. This digital stream needs to be modulated onto an RF carrier by the modulator. Without going into the details of the various types of modulation schemes, a very course categorization of modulation schemes is given here to facilitate the discussion that follows. A first distinction can be made by looking at the bandwidth B of the resulting signal compared to the data rate R. This can either be:

- narrowband: $B \lessapprox R$, or
- wideband: $B \gg R$.

Two examples of narrowband modulation schemes are Quaternary Phase Shift Keying

(QPSK), with $B = R/2$, and Multiple Frequency Shift Keying (MFSK), which for $M = 8$ has a bandwidth equal to $B = 8/3R$. A kind of wideband modulation schemes is formed by spread spectrum schemes. As the name already implies, the spectrum of the signal is spread over a broader bandwidth. There are two main types of spread spectrum modulation schemes (Ziemer, 2007):

- Direct Sequence Spread Spectrum (DSSS),
- Frequency Hopping Spread Spectrum (FHSS).

The two can also be combined into a hybrid modulation technique, but according to Ziemer (2007) there is no need to increase the complexity by doing this, except when resistance to jamming is important. Both techniques have in common that they employ a pseudo-random code to spread the signal equally over the available bandwidth. The resulting signal is then modulated using a "normal" modulation scheme, usually BPSK or QPSK (Proakis and Salehi, 2008). The signal can only be demodulated when this code is known at the receiver, and when the receiver code is synchronized. This makes the receiver more complex, but the increased bandwidth can reduce the signal-to-noise ratio required for demodulation. The gain due to the spreading is called processing gain, which for a direct sequence spread spectrum is equal to

$$G_p = \frac{R_c}{R_s}, \quad (9)$$

where R_c is the chip rate of the pseudo-random code and R_s is the data rate of the signal. When the signal has a data rate of 0.2 Mbps and the chip rate is 10 Mbps, the processing gain is 17 dB. Due to this, a spread spectrum signal is often below the noise level, but after despreading the signal level has increased to a level that demodulation of the resulting BPSK or QPSK signal is possible. This is also the case with GPS signals, which are typically -20 dB below the noise level.

Another distinction between modulation schemes can be made on the basis of the shape of the envelope of the resulting signal:

- constant envelope, or
- varying envelope.

In a modulation scheme with a varying envelope the amplitude of the signal carries information, whereas with a constant envelope the amplitude of the signal does not matter. A signal with a varying envelope can only be processed by a linear circuit. This will limit the options for the amplifiers that are used in later stages, as is discussed in the section on the interface with the Electrical Power System.

When the bandwidth is available, it was shown previously that a signal with a broad bandwidth is more favorable than a narrowband signal in terms of power required. However, higher-order modulation schemes and spread spectrum techniques in particular require more complex transmitters and receivers. The benefits of using a wider band should therefore be traded against a higher complexity. As can be observed in Table 1, where the burst downlink is realized by employing spread spectrum techniques, they can, however, make the system much more efficient.

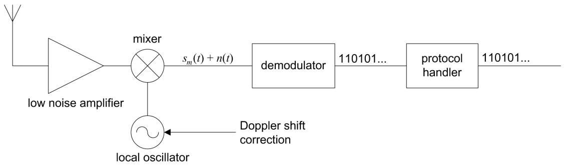

Figure 3: High-level breakdown of a typical receiver.

3.3 RF section

The baseband signal is an analog signal that may be at lower frequencies than the desired transmission frequency. Therefore one or more conversion stages may be required to convert the signal to RF frequency. The output of this stage still has a low power level. Between this stage and the antenna a power amplifier is required to amplify the signal to the necessary power level. The signal from the power amplifier is then fed to the antenna system.

The antenna system is not discussed in much detail here, since the antenna system for nanosatellites will usually consist of one or more dipole antennas or a patch antenna. Apart from the parameter gain this system is not so much driven by system parameters as are other parts of the radio.

3.4 Receiver

A breakdown of a typical receiver is shown in Figure 3. The signal enters the receiver in the antenna system, is amplified to the level required by the rest of the system and then the signal is down-converted if necessary. The frequency of the signal that is received will be different from the frequency of the signal that was transmitted, since the satellite moves with a high velocity relative to the ground station. The resulting Doppler shift must be corrected for. The way this is done depends on the modulation scheme.

After optional down conversion the signal can be demodulated. Together with the signal, also noise has entered the system. At this point the signal-to-noise ratio must be sufficient for correct demodulation. The result of demodulation is a digital bit stream that is equal to the data that was sent by the transmitter, but with a bit error at some places (the ratio of wrong bits and the total number of bits it the Bit Error Ratio (BER)). This digital stream is fed into the protocol handler. The protocol handler reassembles the received frames into data packets. When implemented, error correction and data decompression can be performed. During nominal operation the resulting data stream is equal to the data stream that was fed into the radio system at the other end.

A receiver for spread spectrum signals must include yet another function, which is a synchronization loop. The spreading code of the receiver must be synchronized with the code of the signal. Due to the large distance between satellite and ground station, there will be a delay between the two. This delay will vary as the satellite passes, so the synchronization loop must be tracking continuously. This process requires that the signal includes a known synchronization sequence for the tracker to lock on to. Secondly, some time for synchronization needs to be allowed for, but according to Proakis and Salehi (2008) this is usually only in the order of milliseconds. A bonus is that the variation in delay can be used for ranging purposes.

3.5 Interface with other satellite subsystems

So far only the parameters relating to the communication system itself have been discussed. The communication system is, however, just one of the many satellite subsystems. The communication system has links with the command and data handling system (CDHS), the electrical power system (EPS), and, when directional antennas are used, also with the attitude control system (ACS).

3.5.1 Command and data handling

The role of the CDHS in communications is to accept telecommands from the uplink and to provide telemetry for the downlink. The interface with the communication system is usually formed by an I^2C or CAN bus that is shared by all subsystems. The data rate between the CDHS and the COMMS is determined by the maximum data rate on the bus, the duty cycle of other systems using the bus, and, if no data buffering is used, the transmission data rate.

3.5.2 Electrical power system

In a classical approach the communication system and the electrical power system are designed separately. The interface is typically a voltage line with a fixed level and some provision for switching the transmitter either on and off. The power consumption of the radio is then fixed, and this value is used in sizing the electrical power system, e.g. size of the solar panels and the battery capacity. In this design process it is taken into account that the solar panels and the batteries degrade over time (depending on the mission duration this degradation may, however, be negligible), and that the amount of power that the solar panels generate varies as the attitude of the satellite with respect to the sun varies.

All this results in an electrical power system that is over-dimensioned. At times the satellite will generate more power than is designed for. This extra power needs to go somewhere, and therefore a shunt resistor is often used to dissipate the excess energy (Figure 4). Not only could this energy have been used in a useful way, dissipation also creates a thermal hot spot, and is therefore a concern for the thermal system as well.

There are two ways to approach this problem. The first one is to simply accept that at beginning of life energy is thrown away instead of being used in a useful way. The second approach is,

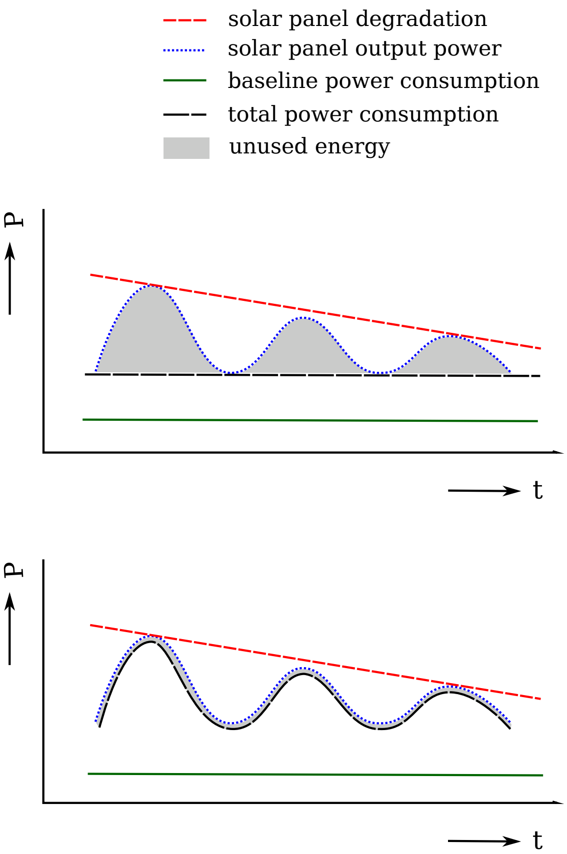

Figure 4: Power curve for a classical EPS (top) and a power-agile system (bottom).

however, more interesting. If the satellite were able to adapt its performance depending on the amount of power available, it would be able to use the available energy to the maximum and no energy needed to be thrown away. This is shown in the second image in Figure 4.

Some systems just consume a certain amount of power. Examples are simple microcontrollers, memory, heaters, reaction wheels and various small electronic parts such as DC/DC converters and bus repeaters. A large microcontroller could increase its clock speed and work at a higher frequency when power is available. Since the difference in power consumption is relatively small compared to other systems, the usefulness of implementing this is only limited.

Another application for the excess energy is to charge the battery at a higher current, but since most batteries have a fixed charge pattern this may not be an option. The batteries also have a limited capacity, and once they are full any excess energy still needs to go elsewhere.

For a typical small satellite this leaves only one system that can really use excess energy: the power amplifier of the transmitter. This is usually also the prime power consumer. When the output of the power amplifier is increased, the extra energy is used to increase the signal strength of the radio signal, which can be used to any of the following advantages:

- The data rate can be increased, or the coding gain of the signal may be reduced to decrease the required processing power. For this a flexible protocol would need to be used; plain AX.25, for example, would not be suitable.
- Less capable ground stations have better signal reception.
- Frame loss is reduced since the bit error rate (BER) is lower.
- Communication time is longer since the signal can be received at lower elevations.

In Section 4 an implementation is discussed of an amplifier that supports variable input power.

3.6 Attitude control system

The attitude control system has an interface with the COMMS when directional antennas are used so that the spacecraft needs to be pointed towards a ground station. A directional antenna has a high directivity D in a specific direction (directivity is related to gain via $G = \epsilon D$, with ϵ the antenna efficiency, of which the impedance mismatch is one component). When the directivity increases, however, the half-power beamwidth decreases, and the pointing requirements become stricter. The directivity is defined as (Balanis, 2005):

$$D(\theta, \varphi) = \frac{4\pi}{\Omega_A}, \tag{10}$$

where Ω_A is the beam solid angle through which all power would flow if the antenna radiation intensity were constant. If the radiation pattern consists of one major lobe and relatively small side lobes, Ω_A can be approximated by Kraus' equation (Balanis, 2005):

$$\Omega_A \approx \Theta_{1\mathrm{r}}\Theta_{2\mathrm{r}}, \tag{11}$$

where $\Theta_{n\mathrm{r}}$ is the half-power beamwidth in radians in direction n. For a symmetrical lobe

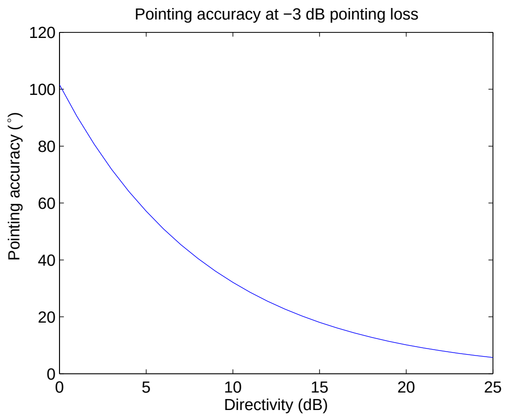

Figure 5: Pointing accuracy required for a maximum pointing loss of -3 dB as a function of antenna directivity.

$\Theta_{1r} = \Theta_{2r} = \Theta$, so that Equation 10 can be reworked to give the half-power beamwidth as a function of directivity:

$$\frac{\Theta}{2} = \sqrt{\frac{\pi}{D}}. \tag{12}$$

This relation is plotted in Figure 5. The quantity $\Theta/2$ can be regarded as the pointing accuracy required for a maximum spacecraft pointing loss of -3 dB. It can be used in a trade-off on pointing requirements versus antenna directivity.

3.7 Properties of a nanosatellite radio

In the following discussion, the two starting points are:

- It is desirable to use the available resources as efficiently as possible under varying conditions.
- It is desirable to make a modular system that has simple and flexible interfaces with other systems and is easy to adapt to varying demands.

Having discussed the communication system and the interfaces with some other spacecraft subsystems, some conclusions can be drawn on properties that are desirable for a small satellite radio.

Data buffering Buffering the data makes the radio flexible: the data rate at which the data handling system delivers the data does not need to be the same as the rate at which data is transmitted. This decouples the communication data rate from the data rate the satellite uses internally.

Data rate adaptation The difference between the E_b/N_0 ratio at the receiver and the E_b/N_0 required to demodulate the signal determines how well the signal is received. The signal-to-noise ratio will vary due to variations in range as the satellite passes over and due to varying atmospheric conditions (e.g. rain and solar wind). If the received E_b/N_0 is not sufficient to demodulate the signal, lowering the data rate could help in restoring the link. Conversely, if the E_b/N_0 is sufficient, the data rate could be increased, much in the same way as WLAN uses variable data rates. While flexible data rates would enable using the satellite at maximum performance under varying channel conditions and available power, it does increase the complexity of the system and poses requirements on the protocol.

Flexible output power The power available on a satellite will vary, but when the transmitter can change its output power, the satellite can transmit data under varying conditions and excess energy will not need to be dissipated. Instead, the only radiating element will be the antenna.

High efficiency power amplifier In small satellites power is limited, and an inefficient power amplifier needs a heat sink to drain the heat produced. This takes up extra mass and volume, and may be an issue for thermal housekeeping. Also in consumer electronics the trend is to use switching power amplifiers to increase battery lifetime.

Flexible frequency Small satellites are usually launched using a piggyback launch. Due to delays in the project a different launch may be selected, which could impose the need to use another frequency.

Flexible coding This is related to varying the data rate. Coding can be applied to lower the BER, but is not necessary when there is sufficient E_b/N_0. If the coding parameters are made flexible the performance of the system can be adapted according to the actual circumstances.

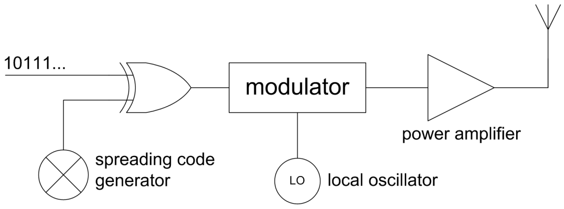

Figure 6: Typical DSSS transmitter.

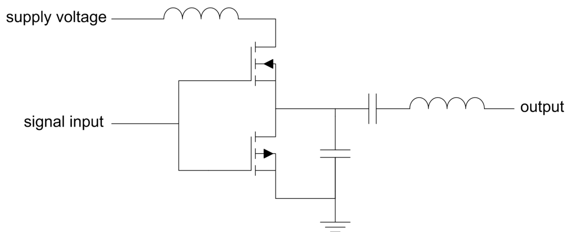

Figure 7: Implementation of a class-E power amplifier that supports agile power output.

4 Delfi-n3Xt

The design principles discussed in the above have been pursued in designing the nanosatellite Delfi-n3Xt. It is the second nanosatellite built by Delft University of Technology, and will carry out eight experiments, one of which is an S-band transmitter (STX). Furthermore, Delfi-n3Xt will carry two other radios, which are similar to the RAP (Radio Amateur Platform) of Delfi-C^3, with UHF uplink and VHF downlink in the radio amateur bands. As a return service for using these bands, Delfi-n3Xt will carry a linear transponder. It is under consideration to use the S-band transmitter in low-power mode for transmitting a beacon continuously. A more detailed description of Delfi-n3Xt is given by de Jong et al. (2008).

4.1 Power agile transmitter

The STX is a transmitter operating at 2.4 GHz that will demonstrate that nanosatellites can be more powerful than they currently are. Direct spread spectrum modulation is used for increasing the bandwidth. See Figure 6 for a schematic view of the transmitter. The bit stream entering the XOR gate comes from the protocol handler. With this transmitter and 500 mW of output power, data rates of 0.5 Mbit can be achieved.

The power amplifier of the STX will be power agile: it transmits with maximum output power. This is implemented by using a switching power amplifier. The input signal is converted into a pulse-width modulated signal that is used to drive the transistors. These switch the power supply on and off at high frequency. Theoretically the efficiency of a switching amplifier is 100%. However, the driver electronics require some power, and for practical systems efficiencies of 86% have been reported (Franco and Katz, 2007). The resulting signal is equal to the input signal in frequency and phase, and the power is determined by the supply voltage. However, if no further measures are taken, amplitude information is lost. For Delfi-n3Xt it has been decided that supporting amplitude modulation is not feasible within the time constraints of the project. From this follows a constraint on modulation scheme that only constant-envelope modulation schemes can be used.

Since the output power of the power amplifier is determined entirely by the supply voltage, it can be used to make a system that uses all the power that is available. The Electrical Power System (EPS) has two outputs: a supply line with a fixed voltage that is used by most systems. The EPS is autonomous, and gives priority to keeping this supply line at a fixed voltage. The EPS also has a second supply line, of which the voltage varies according to how much power is available. It will have a higher voltage when there is excess power available, and zero voltage when there is none. When the power amplifier is active, the switch effectively shorts the supply line and extracts the maximum current. All this power is then radiated, and no excess power is left that would need to be dissipated. In this way, the satellite is able to perform maximally under all circumstances.

4.2 Delfi-n3Xt ground segment

Delfi-n3Xt will use a low-speed downlink (1200 bps) to transmit housekeeping data. The ground segment will be the same as for Delfi-C^3, with a command ground station in Delft and a network of radio amateurs worldwide. In addition to this, the GENSO network may be involved, but this is yet to be investigated. The STX will downlink payload data in one or two bursts every day when passing over the ground station in Delft.

5 Conclusion

Using more bandwidth is the key to a more powerful communication system. Modern electronics now allow designers to do this. It has been shown that transmission in bursts is more efficient than a continuous downlink; that digital processing can increase the data rates that can be achieved; and that using a switching power amplifier allows agile output power so that maximum power is delivered to the antennas at any time.

It has been discussed what the properties are of small satellite radios of the next generation:

- data buffering,
- data rate adaptation,
- flexible output power,
- high efficiency power amplifier,
- flexible frequency,
- flexible coding.

Key to a radio of the future is the ability to adapt to actual conditions, thereby making optimal use of the limited resources that are available to a small satellite.

In addition to defining properties, a top-down approach has been presented for designing such a communication system. Summarizing, the steps to be taken in design time are, in order (steps listed in *italics* are new compared to a classical approach):

1. Determine the orbit geometry.
2. Design the ground segment.
3. *Determine whether downlink is done continuously or in bursts.*
4. *Determine the daily data volume.*
5. Determine the minimum effective data rate.
6. Determine the frequency bands to be used.
7. Determine the bandwidth that can be used.
8. Determine modulation scheme and protocol.
9. Determine the required signal-to-noise ratio.
10. Design the other link parameters such as antenna gain and minimum output power.

The resulting system meets minimum requirements, and these are used to design the interface with other subsystems. This is done in design time. At run time, when the satellite is in orbit, the satellite will adapt to the actual environment by continuously performing the following steps:

1. Determine the available power.
2. Adapt the output power of the power amplifier to use *all* available power.
3. Determine the channel conditions.
4. Choose data rate and coding according to actual channel capacity.

Which of the features mentioned are actually implemented depends on the extend to which the satellite should perform maximally, how complex the system may be and whether other systems such as the electrical power system support these features. However, since the trend is to make satellites smaller and smaller, using the available resources to the maximum will become more and more important, and these features may provide inspiration to the designer of the small satellite radio of the future.

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