Sensor Package Analysis and Simulation for Direct Sensor-to-Satellite Links

***Mohammad J. AL-Saleh* and Amir I. Zaghloul**

Virginia Polytechnic Institute and State University, VA 22043, USA
alsaleh@vt.edu, amirz@vt.edu

Abstract

This paper investigates the design and the performance of low-power micro-sensors that communicate directly to a satellite or a constellation of satellites. Information is spread using pseudo noise (PN). The sensors use a miniature phased array antenna that continuously scans to access the satellite(s). The simulation results show that a sensor as small as 2.35 cm in diameter is able to send information with data rate of 1 kbps at bit error rate less than 10^{-5} to low-earth orbit (LEO) satellites with a transmitted power of 51.3 microwatts (-12.9 dBm) at a frequency of 30 GHz.

1. Introduction

Communication or detection is needed in some unsafe places where no equipment or personnel can reach, e.g. close to volcanoes, in a nuclear activity area, active seismic area or behind enemy lines. Typical remote sensing techniques make it possible to collect data in inaccessible areas but not in non-cooperative environment as it usually requires fixed large equipment that can be easily discovered. Small transmitters are needed to transfer the information with a reliable, secured link. This paper discusses the design of a sensor package that addresses the aforementioned need. The designed sensor will be too small to be easily discovered (as small as 4.34 cm^2 in area). It will sense, transfer data to digital bits, spread the message signal, up-convert to appropriate radio frequency (RF) and send it to low-earth-orbiting (LEO) satellites using phased array antenna that continuously scans its narrow beam to access the available satellite.

The sensor will use satellite links where line of sight is almost always available and the probability of receiving the information by unintended receiver is low. The work consists mainly of two parts: the design of the sensor transmitter up to the antenna which was done using the circuit simulation package Advanced Design System (ADS), and the design of the phased array antenna which was conducted using the software ARRAY. The whole system was then tested by ADS again using a simulated line-of-sight link and a satellite receiver to make sure that its performance meets the required specifications. Real practical numbers for each component parameters were collected from the industry and the literature and used in the simulation.

2. Sensor Design Considerations & Performance

The sensing process depends on the application of the sensor. The sensor output is usually an analog voltage followed by an analog-to-digital converter (A/D) if digital communication is used. In designing the sensor transmitter, random bits are generated to represent the sensor data at the output of the (A/D).

For low data rate satellite communication, techniques like binary-phase shift keying (BPSK) and quadrature phase-shift keying (QPSK) are preferred because of their robustness, simplicity and low cost of implementation. Wireless sensors output data rate is usually 50 – 10000 bps. As the goal was to build a low-cost simple system, with a data rate that does not exceed 10 kbps, BPSK was found to be the best choice in addition to its high power efficiency. Another reason was using direct sequence spread spectrum (DSSS) to encode the signal.

As the application is considered a safety application, a reliable link with low error rate was required. The design procedure started with a goal of final BER of less than 10^{-5}. This value was enough because the assumed data rate did not exceed 10 kbps. Lower BER could be obtained by changing any of the primary elements. From the tables in [1], the required (E_b/N_o) for the BPSK case was found to be 9.9 dB. According to [1], a 0.5 dB margin is considered enough for such systems with low data rate. Satellite engineers usually use a higher margin to cover all the RF losses. Our sensor package didn't include many lossy RF components so a total margin of 3 dB was assumed to cover all other unconsidered losses. The required (E_b/N_o) became 12.9 dB. Thermal noise was considered to be the dominating source of noise at the satellite receiver. In the satellite receiver design, the receiver has a typical system temperature of 500 Kelvin, a value which many commercial satellites use in their receivers [1]. Using the previous value, the theoretical received signal level at the satellite was determined as shown in Table 1 for two different data rates. Calculating the minimum received signal level for each data rate was necessary to determine other important parameters like the transmitted power, code length needed, transmitter antenna gain, and others.

Table 1: Power study at the satellite receiver end for two different data rates

E_b/N_o (theoretical) - dB	9.9	9.9
E_b/N_o (with margin) - dB	12.9	12.9
Noise temperature T_s - Kelvin	500	500
Receiver Noise Figure (NF) - dB	4.4	4.4
Noise spectral density (N_o) - dBW/Hz	-199.6	-199.6
Energy per bit (E_b) - dBJ	-186.7	-186.7
Information Data Rate - bps	500	1000
Received Signal Level (RSL) - dBW	-159.7	-156.7

3. Link Budget

A satellite antenna gain of 20 dB which corresponds to almost 20 degree of beamwidth was assumed. This value along with the path loss was used to determine the minimum effective isotropic radiated power (EIRP) from the link budget equation [1].

$$P_r\ (dB) = P_t + G_t + G_r - Path\ Loss \tag{1}$$

where P_r is the received power, G_t is the transmitting antenna gain and G_r is the receiving antenna gain. EIRP is the product of the transmitter power P_t in watts and G_t in ratio. The *Path Loss* is:

$$Path\ Loss\ (dB) = 20 Log_{10} \frac{\lambda}{4\pi . d} \tag{2}$$

where d is the range to the satellite and λ is the wavelength. Using equations (1) and (2), the minimum EIRP for the sensor transmitter was calculated. Table 2 shows the minimum values needed for the cases of the 780 and 1410 km links with data rates of 500 and 1000 bps at uplink frequency of 30 GHz.

Table 2: Uplink power budget

Data Rate - bps	500		1000	
Received Signal Level - dBW	159.7	-159.7	-156.7	-156.7
Satellite Antenna Gain - dB	20.0	20.0	20.0	20.0
Satellite Altitude - km	1410	780	1410	780
Uplink Frequency - GHz	30			
Min Elevation Angle - degree	18			
Max Slant Range - km	2961.8	1881.6	2961.8	1881.6
Path Loss - dB	191.4	187.4	191.4	187.4
Min EIRP Required - dBW	15.7	11.7	18.7	14.7

Two techniques are used to reduce the needed transmitted power. The first technique is to use a high gain antenna and the second technique is to spread the signal by a PN sequence or Barker code.

4. Spreading

In the designed sensor, DSSS is used with 10^{15}-1chip M-Sequence. Using spread spectrum with such codes gave two main advantages: 1) Coding gain which reduced the required transmitted power. 2) The information was 'encrypted' by using such codes. The coding gain can be defined as:

$$Coding\ Gain\ (dB) = 10\ Log_{10}\ (Code\ Length) \quad (3)$$

The satellite receiver uses a delayed version of the transmitted bits to decorrelate with the received ones and the output is then filtered and applied to a component that measures the BER by trying hundreds of samples. In our simulation using ADS, the available code was PN code with 2^{15}-1 bits M-sequence. This, theoretically, gave a spreading gain of 45.1 dB. Correlation was done by applying the same PN-sequence generator output delayed by the elapsed time the message needs to go from the output of the transmitter modulator to the receiver correlator input.

5. Antenna

Two miniature antennas design are considered in this project. The detailed design of those antennas and the scanning process can be found in [2]. The two models are phased arrays with diameters of 2.35 and 3.35 cm operating at Ka band. The phased arrays scan their beams to find the satellite. The two antennas use circular microstrip patch elements. The two phased arrays are 19- and 37-elements with 0.175 λ element radius and hexagonal sequence. The elements are half-wave length spaced to avoid any grating lobes and so the diameter was 4.7 half-wave lengths or 2.35 cm for the 19-element case, and 3.35 cm for the 37-element. In order to get the highest gain possible, the amplitude distribution is uniform. The highest gain of the 19-element is 18.1 dBi while the highest gain for the 37-element is 20.8 dBi. The polarization amplitudes and phases are set to give a right-hand circular polarization, which is a typical polarization for satellite uplink communications. Duroid substrate is used as it is characterized by a high dielectric constant (epsilon), stability of properties with frequency in the GHz range, small loss angle, and ease of machining. The sensor package is integrated below the antenna surface with a mass distribution that allows the antenna to be facing upward when the package is dropped at random.

6. Transmitter Components Design

The transmitter design starts by a source of binary random bits to represent the digital message from the sensing part. Those bits represent the output of (A/D) at the sensor. The generated bits should include the sensor identity, the message and any other required additional bits. The binary random bits generator output is either 0 or 1 with equal probability. The equal probability of 0s and 1s gives the minimum probability of error at the receiver while deciding whether 0 or 1 was sent. The digital bits are then inserted in a logic-to-non-return-to-zero converter. This component produces the BPSK signal by converting zeros to (– amplitude) and keeping ones (+ amplitude). The complex message signal is then spread by a PN sequence and a multiplier. The PN code generator generates a PN code with 2^{15}-1 bit M-sequence. The resulting signal will have much wider bandwidth than the original signal. Figure 2 shows the major parts of the sensor package.

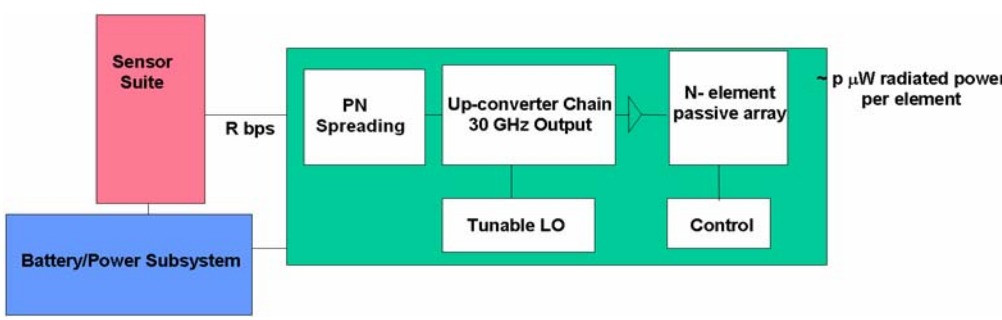

Figure 2: Sensor package

After spreading, the data with the new bandwidth is up-sampled at four times the data rate. The operation of up-sampling is done by the insertion of L-1 zeros between every sample of the input signal, where L is the number of samples produced. The data with the new data rate is then filtered by a finite impulse response (FIR) filter. The filtered data then modulates a carrier of 70 MHz. Two IF stages of up-converting are needed to avoid images. Images are usually filtered using narrow band pass filters. Narrow band pass filters are usually expensive and using them in the sensor is impractical for cost reasons. In the design of both the transmitter and the receiver, each multiplier is followed by a bandpass filter (BPF) to reject images at undesired frequencies. All the filters used in the whole design satisfied the rule; center frequency > 0.02 of the bandwidth of the filter. In general, filters with a center frequency value less than 0.02 of the bandwidth are either very difficult to build, or very expensive, especially at high frequencies. All the filters at the IF and the RF stages are chosen to be Chebyshev filters. The first filter in the IF stage, is centered at 70 MHz, which is the frequency of the previous modulated carrier. The bandwidth of the filter should match the data rate of the signal with the chips. The desired bandwidth can be found using the following known formula for RRC filters [1]:

$$B_{occ} = R_s\,(1+\alpha) \tag{4}$$

where B_{occ} is the bandwidth occupied by the transmitted signal, R_s is the symbol rate and α is the filter roll-off factor. The 40 MHz came from the (data rate x chips length) (1 + roll off factor), assuming a roll factor of 0.2. More than one stage of up-converting is needed for two reasons: to avoid images, and because it is difficult and expensive to built local oscillators and filters at wide bandwidths. The second local oscillator generates a frequency of 1430 MHz to up-convert the signal to a frequency of 1.5 GHz. The two values for the IF stages frequencies were brought from industry. Most of the RF communication systems use the 70 MHz as a first stage. The second stage usually takes place between 1-2 GHz; this makes the up-converting process more efficient. The two chosen values are supposed to make the fabrication process less expensive by benefiting from the mass production of the components at these frequencies. Another BPF centered at 1.5 GHz is used after the local oscillator with 1430 MHz. This filter has to be wider since its center frequency is higher. 100 MHz is chosen as a suitable bandwidth of this filter.

As the frequency of transmission is set to 30 GHz for the uplink Ka-band antenna, the last local oscillator produces a 28.5 GHz carrier. The last filter is set to the frequency of 30. As the spectrum output components of the last multiplexer are at (28.5 ± 1.5) GHz, major images from this stage would be at 27 GHz. The bandwidth of the last filter is set to 1200 MHz to filter out the image component. After the 30 GHz BPF, the signal becomes ready to be sent to the satellite. An RF amplifier with 3 dB gain doubles the power of the signal and the output is connected to the phased array antenna input port.

7. Simulation Results

Running the simulation for the 1000 bps data rate using the 37-element array with transmitted power of 13.8 μW (-18.6 dBm) and 1410 km link, the resulting BER was ~ 1.6×10^{-4}, which is worse than the theoretical one. This is due to many factors: many components in the transmitter and the receiver can add noise to the signal; the filters might not have ideal characteristics and the amplifiers nonlinearity. Although a BER of 1.6×10^{-4} is considered acceptable for this application at data rate of 1000 bps, it is desirable to increase the transmitted power by few dBs to increase the carrier-to-noise ratio (C/N) at the receiver for less errors and a more reliable system.

In order to get the desired performance, 3 dB was added to the transmitted power and the simulation was rerun, resulting in a mean BER of ~ 7.3×10^{-6}, which exceeds our goal of 1×10^{-5}. In general, the real performance will be much better as these values are based on the worst case assumptions. For the 19-element antenna, the same design applies but 2.7 dB more will be needed at the transmitter output power to compensate for the antenna gain difference, with a net power of 51.3 μW or -12.9 dBm. Fewer scanning steps will be required for the 19-element arrays to cover the same space due to its wider beam compared with the 37-element antenna beam.

8. Conclusions

The simulation results and analysis in this paper have shown the ability to design a sensor as small as 2.35 cm in diameter that is able to sense different information and send the related data to LEO satellites with very low power and high efficiency. The designed sensor has a low cost and provides a reliable link. Using a phased array antenna and DSSS signal reduced the needed transmitted power dramatically.

9. References

1. T. Pratt, C. Bostian, and J. Allnutt, *Satellite Communications*. 2nd ed. Hoboken, NJ: J. Wiley & Sons, 2003.

2. M. AL-Saleh, A. Zaghloul, "Miniature Antennas for Direct Sensor-to-Satellite Links," *2008 IEEE, International Symposium on Antennas and Propagation.* San Diego, July 2008. (in review).