DESIGN CONSIDERATIONS FOR DIRECT RF SAMPLING RECEIVER IN GNSS ENVIRONMENT

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ABSTRACT

In this paper, an advanced direct RF sampling receiver architecture is studied for the GNSS environment. The architecture is based on sampling the signal directly at RF, which in the GNSS case are in the 1.5 GHz range. The high-frequencies in the signals to be sampled pose then very high demands for the accuracy and quality of the sampling process, and thus quantization and especially the timing jitter must be considered in detail. The study shows that the quantization and jitter requirements are, however, feasible when the pre-sampling filtering is done properly.

1. INTRODUCTION

Not only the wide scale changes in technology of Global Navigation Satellite Systems (GNSS), but also the demand for low-cost and flexible GNSS receivers has been greatly increasing in the last few years in many application areas. Car navigation systems are becoming almost an essential part of better-class cars, and the demand for GNSS integrated cellular phones is also increasing [5]. The car navigation systems need to be as cheap as possible and cellular phone integrated navigation systems must also be small and have low power consumption. In addition, as the cellular phones of course need receivers for capturing the cellular signals, there is big interest to receive Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and GPS/Galileo signals, all with one flexible receiver.

Direct RF Sampling (DRFS) receiver architecture is one promising approach for building flexible radio receivers. The idea of DRFS is to sample the signal at as early stage of the receiver as possible. The down-conversion of the high-frequency signals can be done within the sampling process itself, using aliasing in a controlled manner. So there is no need for analog mixers and thus the analog component count decreases. Analog components are usually bulky, expensive and use quite much power so the basic concept of the DRFS gets very interesting. In addition, the flexibility of the DRFS receiver is at a very high level because the signal is sampled directly from the radio frequencies (RF). Naturally, the signal must be filtered before sampling but the filtering can be done so that the signals of more than one communications systems can be processed and received. The topic of DRFS has not yet been thoroughly investigated and there are only a few papers that consider the practical implementation of the DRFS receiver principle. Thus, the idea is very promising but more research needs to be done on the topic. The direct RF sampling receiver architecture has been considered in [1], [2] and [12] with focus on the GNSS case, and more generally in [4].

One of the main problems in a DRFS receiver is the high demands for the quality of the sampling process due to the high frequency of the sampled signals [6], [15]. This paper concentrates on the requirements the DRFS receiver has for the sampling process in GNSS application. First, the sampling jitter and the quantization effects on the signal-to-noise ratios (SNR) are considered. Then, the sampling jitter and quantization level requirements for the sampling of a GNSS signal centered at 1575.42 MHz (E2-L1-E1) band are considered. After the requirements have been derived by using system calculations, the results are verified using simulations.

2. BASIC NON-IDEALITIES IN SAMPLING

The main sources of noise in a sampling system are the limited number of bits in the quantization and unintentional deviations called jitter in the moments the samples are taken. Limits in these non-idealities are of interest when a high-performance sampling system is needed in demanding environments such as in DRFS receiver [13]. For system calculations, we focus on power spectral densities (PSD) of the noise components generated in the sampling process. In this chapter, PSD's for quantization and jitter noise are determined. These are then used in Chapter 3 for deriving the quantization and jitter requirements for capturing the GNSS signal using the DRFS principle.

2.1. Quantization Noise

The most basic non-ideality in a sampling system is the quantization noise. If a sampled signal has values from −1 to 1 and *n* bit quantization is used, the possible error value is uniformly distributed between -2^{-n} and 2^{-n}. Thus the power of the quantization noise is

$$\mathrm{var}(e(i)) = \frac{2^{-2n}}{3}$$

where *e(i)* is the error of the *i*-th sample. Assuming a sinusoidal signal with root mean square (RMS) power of $(V_{rms})^2 = 1/2$, the SNR due to quantization can be written as:

$$SNR_{quant} = \frac{1/2}{2^{-2n}/3} = \frac{3}{2}2^{2n}$$

In quantization, the white noise model is considered to be valid and thus the PSD of the quantization noise can be written as:

$$PSD_{quant}(f) = \frac{P_{quant}}{F_s} = \frac{P_{signal}}{SNR_{quant}F_s} = \frac{2P_{peak}}{3F_s 2^{2n}} \qquad (1)$$

In the final form, we have substituted $P_{signal} = P_{peak}$ since the peak power is the critical quantity in quantization. White noise naturally falls to the bandwidth determined by the sampling rate F_s.

The calculations of quantization noise are based on the basic signal processing work done by Huttunen in [10], and by Tsui in [14].

2.2. Jitter Noise

As the frequencies of the sampled signals rise, the timing of the sampler becomes a limiting factor in the performance of the sampling process [3], [13]. In this section, we study the contribution the noise generated by the timing jitter has on the performance of the total system.

The jitter noise naturally depends on the shape of the signal we are sampling. Because the transmitted modulated signals are of oscillating nature in telecommunications, we can assume for analysis purposes that the interesting signal is a sinusoidal signal as well. Thus, its voltage can be presented as $V(t) = A\cos(2\pi f_0 t)$. With this assumption, we are able to calculate the voltage error of the signal when we consider only the error due to the jitter. In the jitter analysis, we use the RMS value of the timing jitter. Let us first calculate the RMS value of the derivate of *V:*

$$\left.\frac{\delta V}{\delta t}\right|_{rms} = \sqrt{\frac{1}{T}\int_0^{T_0}\left(\frac{\delta V(t)}{\delta t}\right)^2} = \sqrt{2}A\pi f_0$$

In this equation, $T_0 = 1/f_0$ is the cycle time of the sinusoid. When we multiply the RMS value of the voltage derivative by the RMS value of the jitter Δt, we get the voltage error, which is $\sqrt{2}A\pi f_0\Delta t$. Then, by dividing the signal power by jitter noise power, the SNR due to jitter is of the form:

$$SNR_{jitter} = \frac{\left(A/\sqrt{2}\right)^2}{\left(\sqrt{2}A\pi f_0\,\Delta t\right)^2} = (2\pi f_0\Delta t)^{-2}$$

In [13], Shinagawa et al have done some calculations with the same results and noticed that this model is as accurate as expected. Now that the SNR_{jitter} is calculated and we have got rid of the amplitude term, the power of the jitter P_{jitter} can be calculated as

$$P_{jitter} = P_{total} / SNR_{jitter}$$

Then if the jitter noise is considered to be white noise and thus spread over the Nyquist band, we can get the PSD of the jitter noise as

$$PSD_{jitter}(f) = \frac{P_{jitter}}{F_s} = \frac{P_{total}(2\pi f_0\Delta t)^2}{F_s} \qquad (2)$$

Similar results are got by Valkama et al. in [16].

3. JITTER REQUIREMENTS IN DIRECT RF SAMPLING RECEIVER

One possible approach to determining the jitter requirements in a GNSS receiver was introduced by Dempster in [6]. The approach is very simple and is based on the basic properties of the GNSS signals. As is known, the GNSS signals are under the thermal noise level. GPS signal is not expected to exceed −150 dBW in any situation [11] and is thus under the thermal noise with its about 2 MHz bandwidth. Also, Galileo signal specifications say that its signals in E2-L1-E1 band are not expected to exceed −148 dBW [8], and have wider bandwidth of interest than signals of the GPS. The

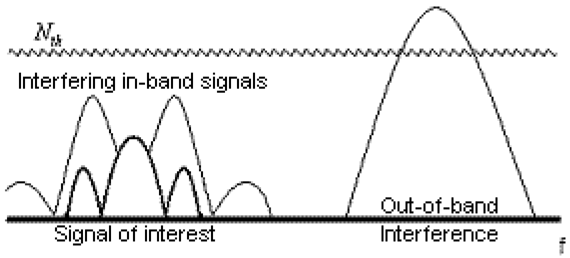

Figure 1: The noise-dominated environment. The signal with thicker line is the signal we are interested in.

Galileo signals are also under the thermal noise. Thus, when sampling a GNSS signal at RF, the sampled signal practically consists of the thermal noise or other interferences that are not filtered out. As was shown in Equation (2), the power of the jitter noise depends on the overall power of the sampled signal. Now, if the noise generated by the jitter is say 10 dB under the thermal noise, its contribution to the total system noise can be considered insignificant. The situation explained here can be seen in Figure 1. The thermal noise is at a higher level than the interesting signals and interfering in-band signals. In addition, some out-of-band interference signals may be present.

Although ideally the signal we take samples from is thermal noise, there might be other interfering signals present if our pre-sampling filtering is not selective enough. In addition, stronger other GNSS signal might interfere with the current signal of interest. Therefore, in determining the overall power of the sampled signal, these other signals need to be taken into account. There is thus interest to study cases where the total sampled power is, for example, 10 dB, 20 dB and 30 dB over the thermal noise, to make sure the study is surely extensive enough. This means that the total sampled power P_{total} can be written as:

$$P_{total} = N_{th}(1+x) = N_{th} + xN_{th}$$

in which x represents how many times stronger the overall out-of-band interference is, compared to the thermal noise. For 10 dB, 20 dB and 30 dB the values of x are 10, 100 and 1000 respectively. The PSD of the thermal noise itself is [7]:

$$PSD_{th}(f) = \frac{1}{2}kT$$

The jitter requirements for voltage sampling can then be derived from the equation:

$$PSD_{jitter}(f) \le \frac{1}{10} PSD_{th}(f) \qquad (3)$$

Thus, the jitter requirement can be written, with help of Equation (2) and Equation (3), in the following way:

$$\Delta t \le \sqrt{\frac{F_s}{20 \times B(1+x)(2\pi f_0)^2}}$$

Now by denoting the oversampling factor $osf = F_s / B$ in the equation, the simplest form can be achieved without the bandwidth term:

$$\Delta t \le \sqrt{\frac{osf}{20 \times (1+x)(2\pi f_0)^2}} \qquad (4)$$

By using Equation (4), we get the basic results for the jitter requirements. The results are here calculated for oversampling factors of four and eight as thought realistic in band-pass sampling. These correspond to sampling rates of 120 MHz and 240 MHz with signal bandwidth of 30 MHz, which should be enough for Galileo reception [1], [9]. Calculating the results for more oversampling factors is a trivial process.

As the results in Table 1 show, if there is no external interference in the system, the requirements are not so tight at all, but when the interference increases, the requirements get tighter and tighter. Novel low-power analog-to-digital converters and samplers have RMS jitter value of about two picoseconds [4]. Therefore, the tightest requirement with oversampling factor of eight is still achievable but that would be quite tightly in the limits. In interference-free environment, the sampling jitter requirements would not be hard to achieve, but getting such a semi-ideal environment would result in very high requirements for the selectivity of the front-end filters. With more power-consuming analog-to-digital converters and samplers, all the calculated requirements are easily achievable, but the practical implementation in mobile receivers could not yet be done with the technology of today.

4. QUANTIZATION REQUIREMENTS IN DIRECT RF SAMPLING RECEIVER

The quantization requirements can in principle be calculated in a rather similar way as the jitter requirements. If the quantization noise is 10 dB under the thermal noise, the contribution is no more than that of the jitter noise in the same situation. As the Equation (1) shows, the quantization noise power depends essentially on the peak power of the sampled signal. Thus, the difference between the jitter and the quantization study is that as the jitter noise depends on

Table 1: The jitter requirements for voltage sampling DRFS receiver

P_{total} / N_{th}	Oversampling factor	
	4	8
0 dB	45.2 ps	63.9 ps
10 dB	13.6 ps	19.3 ps
20 dB	4.50 ps	6.36 ps
30 dB	1.43 ps	2.02 ps

Table 2: The quantization requirements for DRFS receiver.

P_{total} / N_{th}	Oversampling factor	
	4	8
0 dB	2.53 (3) bits	2.03 (3) bits
10 dB	4.26 (5) bits	3.76 (4) bits
20 dB	5.86 (6) bits	5.36 (6) bits
30 dB	7.51 (8) bits	7.01 (8) bits

the total sampled power, the quantization noise depends on the peak power of the signal. This is natural because the highest signal amplitude must have its own level in the quantization process. We also know that in the GNSS environment, we practically sample band-pass noise whose crest factor is around 10 (peak / RMS). We can thus write:

$$P_{total} = 1/10 \times P_{peak}$$

Putting all these together the requirement for the quantization accuracy can be formulated as

$$n \geq \log_2\left(\frac{400 \times (1+x)}{3 \times osf}\right)/2 \qquad (4)$$

The requirements can be directly evaluated from the Equation (4). The results can be seen in Table 2.

As the results in the table demonstrate, the quantization requirements are from two to eight bits depending on the case. The requirements are not so high and are achievable with novel low-power analog-to-digital converters. The quantization noise does not act as strong limiting factor in a DRFS receiver as the sampling jitter noise does.

5. JITTER REQUIREMENT VERIFICATION

Next, our target is to verify by simulations the jitter calculations we made in the previous sections. The fact that the jitter requirements were obtained only by using the system calculation principles, leaves the results floating a little. Even though the used equations are verified with simulation in the references, the results we got should also be verified. As we saw in the results in Table 1, 63.9 ps jitter is enough for us to get the jitter power 10 dB under the sampled pass-band noise signal power if oversampling factor of 8 is used. Now we will verify this result.

We make a simulator with MathWorks Matlab 7. In the simulator, a band-pass-noise signal with 29.6875 MHz bandwidth at E2-L1-E1 band (1575.42 MHz centered) is sampled. We use a 3.8 GHz sampling rate in the actual jitter simulation stage and the signal is then decimated without filtering to get a sampling frequency of 237.5 MHz. This is equivalent for the oversampling factor of eight for a bandwidth of 29.6875 MHz. Due to the decimation by 16 without filtering, the jitter noise aliases to lower frequencies as it would have aliased if the 237.5 MHz sampling frequency would have been used in the first place. The spectrum at the simulator output can be seen in Figure 2.

The simulations clearly verify the fact that the jitter noise stays 10 dB under the thermal noise with 63.9 ps sampling jitter in case of oversampling factor of eight.

In addition, let us verify one more case with oversampling factor of 4. This is equivalent with decimation by 32. Thus the sampling rate is 118.75 MHz. In this case, the sampling jitter of 45.2 ps should take the jitter noise 10 dB under the interesting signal. The results are shown in Figure 3. It can be seen that the jitter noise is, indeed, 10 dB under the band-pass-noise signal and thus the jitter requirements seem to be valid for both oversampling factors used in calculations.

5. CONCLUSIONS

We have studied the jitter noise and quantization noise effects in the sampling and A/D process with special focus on direct RF sampling receiver in GNSS context, and derived the equations for power spectral densities of such noises. Furthermore, the equations for jitter and quantization requirements for direct RF sampling receiver in GNSS environment were derived. It was assumed that if the power of the sampling noise is 10 dB under the thermal noise, the contribution to the total system performance is diminishing. The jitter and bit-resolution requirements were considered in a few realistic situations. The results showed that if the selectivity in the RF filters is good enough, the bit and jitter requirements are feasible. On the other hand, if the pre-sampling filtering is not done properly, the requirements for the jitter rise to levels that are not yet practical in mobile communications devices, at least with today's techniques. The jitters of around, or less than, one picoseconds are achievable with high-power analog-to-digital converters of today but are by no means practical in mobile devices due to high power consumption. The resolution requirements seemed quite relaxed even with high interfering signal levels. Practically, eight bits would be enough even in very demanding applications.

Simulations verified that with the calculated sampling jitter requirements, the jitter noise stayed 10 dB under the thermal noise, which was used as the design principle in jitter calculations.

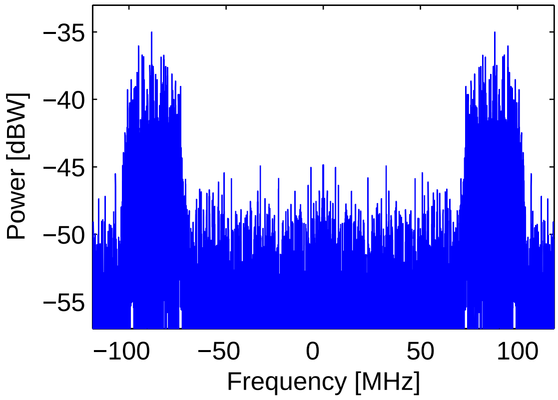

Figure 2: Band-pass-noise signal sampled with 237.5 MHz sampling rate with 63.9 ps sampling jitter.

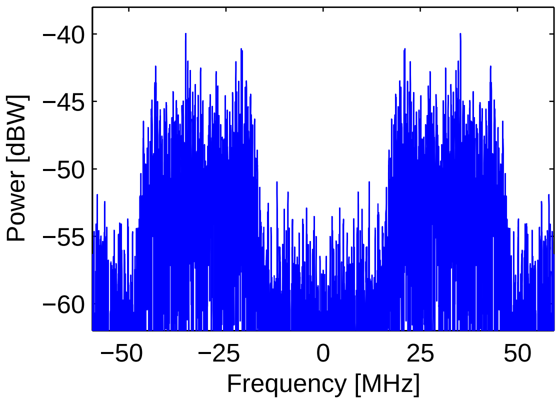

Figure 3: Band-pass-noise signal sampled with 118.75 MHz sampling rate with 45.2 ps sampling jitter.

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