Non Uniform Sampling for Power Consumption Reduction in SDR Receiver Baseband Stage

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Abstract

In this paper, authors point out the effect of non uniform sampling (NUS) on the power consumption in SDR receiver baseband stage. This feature is drawn by theoretical formulas regarding spectrum shape and power estimation of different baseband components. An example is drawn to focus on NUS ability to reduce anti-aliasing filter (AAF) consumption by 25%.

1. Introduction

Following the huge growth of wireless means of communication, radio terminals have to support more standards and consume less power. Within software defined radio (SDR) conditions related to meet many standard requirements and handle several hard constraints, receivers must be more reconfigurable and less power consuming [1].
In this paper, authors present the non uniform sampling (NUS) as a solution to reduce power consumption while sampling. This feature is proved by evaluating baseband power consumption estimation and presenting theoretical formula of NUS alias reduction. Examples are then drawn to point out the NUS power consumption reduction feature.

This paper encloses three parts. In section 2, baseband stage power consumption estimation is presented. Theoretical formulas taken from literature are summarized in this section. Section 3 involves NUS definition and presentation of time-quantized random sampling (TQ-RS), a NUS scheme devoted to implementation. In section 4, TQ-RS ability to reduce power consumption has been shown.

2. Baseband Stage Power Consumption Estimation

Three main components form the baseband stage of SDR receiver. The anti-aliasing filter (AAF) gets rid of all interferers and blockers that could be folded over the signal after sampling operation. The automatic gain control (AGC) should tune all signals amplitude in order to present sufficient dynamic range (DR) at the input of analog-to-digital converter (ADC). ADC performs the conversion from analog to digital mode.

2.1. Anti-aliasing filter

Considered sampling frequency is f_{ADC} and considered bandwidth signal is B_c. If a blocker with an amplitude of N_{bl} is situated in the interval $[f_{ADC}, f_{ADC} - B_c/2]$, it will be folded over the signal after sampling. The AAF role is to attenuate all the blockers over $f_{ADC} - B_c/2$. At this frequency, the attenuation must be at least equal to A_{min} given by Eq (1) and presented by Fig. 1.

$$A_{min} = N_{bl} - S_t + SNR_{out} + M_{AAF} \tag{1}$$

where S_t is the test signal, the SNR_{out} the required signal-to-noise ratio (SNR) and M_{AAF} a margin of 3 dB.
In addition to the cost constraints directly related to AAF order n_P, terminal portability puts a condition on the power consumption. AAF power consumption P_{AAF} is estimated as given by Eq (2) [2].

$$P_{AAF} = P_{POLE} \cdot n_P \tag{2}$$

where P_{POLE} is the AAF power dissipation per pole. P_{POLE} value has been estimated via simulations considering different standards as summarized in Table 1[2].

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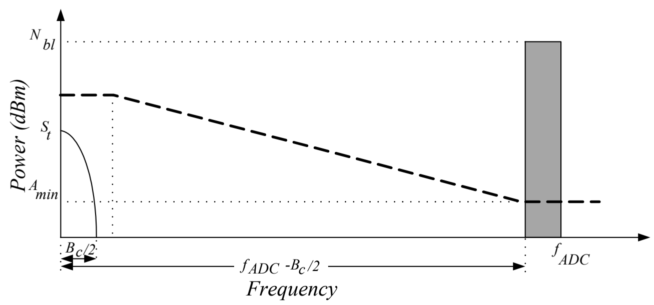

Figure 1. AAF role to avoid blocker folding over signal.

Table 1. Power per pole of channel select filter for IEEE802.11a, DVB-H and UMTS.

Standard	$B_c/2$ (MHz)	P_{POLE} (mW)
IEEE802.11a	8.33	2.4
DVB-H	3.8	1.1
UMTS	1.92	0.6
IEEE 802.11.j	4.15	1.3

2.2 Automatic Gain Control and Analog-to-Digital Converter

The automatic gain control is used to adjust the signal to maintain its level within some desired range. The gain is then variable according to the input. The minimal and maximal AGC gain is presented by Eq (3). All AGC gain parameters depend of ADC and other receiver components [3].

$$\begin{aligned} G_{AGC_{min}} &= S_{FS} - S_{max} - G \\ G_{AGC_{max}} &= S_{FS} - \left(N_{bl_{max}} - Att\right) - G \end{aligned} \tag{3}$$

where S_{FS} is the ADC full-scale, S_{max} is the signal maximum input power, G is the total analog gain before mixer block in a conventional receiver architecture and $(N_{bl_{max}} - Att)$ refers to the power of the strongest blocker after all filters attenuation before AGC. The maximal amplitude in a standard band is amplified by $G_{AGC_{min}}$ to avoid ADC saturation. The little signal power is amplified by $G_{AGC_{max}}$ in order to reach ADC full-scale. In this case, the amplification must take into account blockers power at AGC input to avoid saturating ADC. The more AGC provides gain, the more ADC number of bit N should be reduced as presented in Eq (4).

$$N = \frac{\left(DR_{ADC} + G_{AGC_{min}} - G_{AGC_{max}}\right) - 1.76}{6.02} \tag{4}$$

The ADC is often the most power consumer in the SDR receiver baseband stage. Its power consumption exponentially depends of N as presented by Eq (5) [2, 4].

$$P_{ADC} = E_{conv}\ f_{ADC}\ 2^N \tag{5}$$

where E_{conv} is the energy required per conversion step and depends on the ADC technology. Its values are around few picojoules. For instance, E_{conv} is less then 1pJ for 0.65 nm²-CMOS technology. Eq (5) seems to be incoherent with current converters. In [5], a 12-bit ADC implemented on 90 nm² CMOS technology consumes 3.5 mW and samples at $f_{ADC} = 100$ MHz . Also, a 10-bit , 0.13 µm²-CMOS implemented ADC consumption is equal to 0.92 mW. Its sampling frequency is $f_{ADC} = 50$ MHz [6]. In order to maintain reducing power consumption, NUS alias reduction feature is proposed to enhance energy saving.

3. Non Uniform Sampling

The non uniform sampling is a kind of signal processing in which irregular sampling instants are considered. NUS converts continuous analog bandpass signal into its discrete representation. Assuming a continuous signal $x(t)$, its discrete representation $x_s(t)$ is given by Eq (6).

$$x_s(t) = x(t) \sum_{k=-\infty}^{k=+\infty} \delta(t - t_k) \tag{6}$$

In NUS case, sampling instants are defined as $t_k < t_{k+1}$ with $T_{ADC_{mean}} = 1/f_{ADC_{mean}}$ is the mean sampling period and $f_{ADC_{mean}}$ the mean sampling frequency. NUS promises alias elimination or at least reduction by considering specified conditions on the sampling instants [7].

According to the construction of the sampling instant sequence, several types of NUS could be defined. The time-quantized random sampling (TQ-RS) is the NUS technique scheme devoted to implementation. In fact, TQ-RS considers quantized sampling instants with quantization step $\Delta = \frac{T_{ADC_{mean}}}{q}$ where q, the quantization factor, is the number of possible values that the instant sampling period could take within $T_{ADC_{mean}}$. In other works, authors proved that, if anti-aliasing conditions are respected, an estimation of Fourier transform of TQ-RS sampled signal is given by Eq (7) [8].

$$\hat{X}_s(f) = X(f) \circledast \left[\left(1 - e^{-j\pi f T_{ADC_{mean}}\left(1-\frac{1}{q}\right)} \mathrm{sinc}\left(\pi f T_{ADC_{mean}}\right)\right)\right] + \frac{1}{T_{ADC_{mean}}} e^{-j\pi f T_{ADC_{mean}}(1-1/q)} \mathrm{sinc}(\pi f T_{ADC_{mean}}) \sum_{k=-\infty}^{k=+\infty} X\left(f - \frac{k}{T_{ADC_{mean}}}\right) \qquad (7)$$

This formula shows the TQ-RS ability to reduce replicas. In fact, the second term of (6) shows that the replicas located at $X\left(f - \frac{k}{T_{NUS}}\right)$ are attenuated by the sinc function presented in Fig. 3.

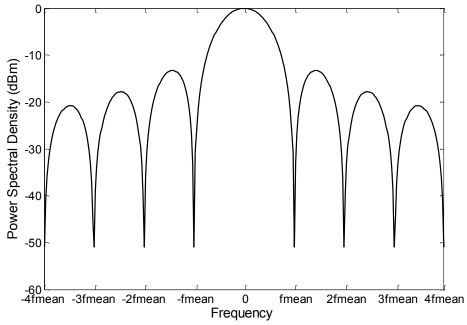

Figure 3. Alias reduction function applied to Fourier transform of TQ-RS sampled signal.

For sake of readability in Fig. 3, authors rename $f_{ADC_{mean}}$ by f_{mean}. It can be noticed that all the noise could be considerably attenuated in the intervals $\left[kf_{ADC_{mean}}/2, (k+1)f_{ADC_{mean}}/2\right]$ with $1 \le k < q$. This feature is then used to reduce constraint on SDR receiver components especially AAF by reducing A_{min} by the TQ-RS attenuation Att_{TQ-RS}. This will then release constraints on AAF and consequently decreases its order and its consumption.

4. Examples of TQ-RS Power Consumption Reduction

Authors propose in this section to point out the effect of TQ-RS sampling on SDR receiver components. The baseband receiver architecture on which power consumption estimation will be achieved is a multistandard hybrid low-IF/zero-IF architecture. The GSM/UMTS/IEEE802.11a receiver includes 4th order Butterworth AAF. GSM canal is located after down-conversion at 0.2 kHz whereas UMTS and IEEE802.11a are centered at zero. The power consumption reduction study includes AAF, AGC and ADC.

4.1 AAF Consumption Reduction

In the considered baseband, AAF is a 4th order Butterworth filter. Different sampling frequencies are selected for each standard. The estimated power consumption of each filter is summarized in Table 2. In GSM case, P_{POLE} is estimated to 0.1 mW. Considering the same baseband architecture and the same sampling frequency f_{ADC}, TQ-RS alias attenuation feature allows reducing the minimal attenuation A_{min} by Att_{TQ-RS} computed through Eq (6). In table 2, it can be noticed that AAF order is reduced for both UMTS and 802.11.a.

Table 2. AAF specifications for GSM/UMTS/IEEE802.11.a for uniform and TQ-RS sampling.

	Uniform sampling			Non uniform sampling		
Standard	GSM	UMTS	802.11.a	GSM	UMTS	802.11.a
f_{ADC} (MHz)	3	15	50	3	15	50
Cut-off frequency (MHz)	0.2	1.92	8.3	0.2	1.92	8.3
Rejection frequency (MHz)	2.8	13.08	41.7	2.8	13.08	41.7
N_{bl} (dBm)	-33	-56	-47	-33	-56	-47
Att_{TQ-RS} (dB)	0	0	0	15.6	12.5	9.2
A_{min} (dB)	78	42.8	44.6	62.4	30.3	35.4
AAF order for uniform sampling	4	4	4	4	3	3
P_{POLE} (mW)	0.1	0.6	2.4	0.1	0.6	2.4
AFF estimated power consumption (mW)	0.4	2.4	9.6	0.4	1.8	7.2

Thanks to TQ-RS sampling, replicas decreases allowing to save power. Power consumption is reduced by 25%.

4.2 Study of AGC and ADC power consumption in NUS case

NUS effect on SDR receiver baseband stage is reducing AAF order. Thus, at AGC input, blockers are less reduced then in uniform sampling case. For example, in 802.11.a standard, the power of the strongest blocker after AAF attenuation, $\left(\mathrm{N_{bl_{max}}} - \mathrm{Att}\right)$, is located at 20 MHz and equal to -63.81 dBm in NUS sampling case and -65.31 dBm in uniform sampling case. Assuming $\mathrm{G} = 43$ dB and $\mathrm{S_{FS}} = 13$ Bm, AGC maximal gain $\mathrm{G_{AGC_{max}}}$ is then equal to 33.81 dB for a 3rd order AAF and 35.31 dB for a 4th order AAF. Computed ADC number of bits N is then unchanged for uniform and NUs sampling. It is equal to 6 bits for both cases. ADC and AGC power consumption is almost not affected by NUS.

For SDR multistandard receiver, ADC dynamic range $\mathrm{DR_{ADC}}$ is equal to 96 dB, 73.8 dB and 61.8 dB for GSM, UMTS and 802.11.a respectively. In that case, a 12-bit ADC could be used to digitize UMTS and 802.11.a signal without AGC. However, GSM signal has to be amplified by $\mathrm{G_{AGC}} = 22$ dB . Such AGC is implemented on 0.35 µm²-CMOS technology and consumes 2.4 mW [9]. The total power consumption is then equal to 6.9 mW, 5.9 mW and 13.1 mW in uniform sampling compared to 6.9 mW, 5.3 mW and 10.7 mW for GSM, UMTS and 802.11.a respectively. Saving power on AAF allows reducing 10% of the total power consumption for UMTS and 17.5 % for 802.11.a.

5. Conclusion

In this paper, theoretical formulas of power consumption estimation for AAF and ADC are given. The NUS power consumption reduction feature is shown on SDR receiver baseband components. NUS allows saving up to 17.5% of total baseband power consumption. Authors' perspectives are to explore the eventual possibility of NUS power reduction of AGC or ADC. This must be started by a careful study of AGC and ADC architectures adaptable to NUS methodology.

6. References

1. J. Mitola, "Software radios: survey, critical evaluation and future directions," IEEE Aerospace and Electronic Systems Magazine, vol. 8, no. 4, pp. 25-36, Apr. 1993.

2. V. Giannini, J. Craninkx, A. Baschirotto*, Baseband Analog Circuits for Software Defined Radio,* Springer, ISBN 978-1-4020-6538-5, 2008.

3. R. Barrak, *Récepteur radio multistandard à conversion de fréquence par sous-échantillonnage RF*. Ph.D. thesis. CIRTA'COM, SUP'COM Tunisia. February 2007.

4. J. Jussila, *Analog Baseband Circuits for WCDMA Direct-Conversion Receivers*. Ph.D. thesis, Helsinki University of Technology.

5. J. Chu, L. Brooks, and H.-S. Lee, "A Zero-Crossing Based 12b 100MS/s Pipelined ADC with Decision Boundary Gap Estimation Calibration", Symposium on VLSI Circuits/Technical Digest of Technical Papers,ISBN: 978-1-4244-7641-1, pp 237-238, 2010.

6. Chun-Cheng Liu, Soon-Jyh Chang, Guan-Ying Huang, Yin-Zu Lin , "A 0.92mW 10-bit 50-MS/s SAR ADC in 0.13µm CMOS Process", Symposium on VLSI Circuits Digest of Technical Paper, vol 23, no 1, pp236-237, 2009.

7. I. Bilinskis, A. Mikelsons, *Randomized Signal Processing*, Prentice Hall, 1992, ISBN 0137510748.

8. A. Maalej, and al. "Time-Quantized Random Sampling for Alias Reduction", submitted to Newcas 2011 conference.

9. J. P. Alegre, B. Calvo, S. Celma, "A High Performance CMOS Feedforward AGC Circuit for Wideband Wireless Receivers", IEEE international Symposium on Industrial Electronics, ISIE ISBN : 978-1-4244-1666, pp 1657-1661, 2008.