Autonomous Operation of Super-Regenerative Receiver in BAN

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Abstract— **Super-regenerative receiver is one of the potential candidates to achieve ultra low power wireless communication in body area network (BAN). The main limitations of the super-regenerative receiver include the difficulty in choosing a good quench waveform to optimize its sensitivity and selectivity, and its significantly degraded performance in the presence of interference. To address the above problems, we first propose a novel quench waveform search algorithm providing good sensitivity and selectivity results. The algorithm avoids the undesirable manual calibration and hence suitable for autonomous operation. In addition, we consider the spectrum sensing algorithm to autonomously avoid data transmission in the presence of unacceptable interferences. The above algorithms enabling autonomous operation of the super-regenerative receiver are implemented in hardware. Our measurement results show that by using the quench waveform calibrated super-regenerative receiver, the system can provide stable probability or mis-detection and probability of false alarm results in different carrier frequencies. This is very desirable for the determination of a good threshold in spectrum sensing. Together with our previously reported chip designed for the super-regenerative receiver, we have developed an autonomously operating super-regenerative receiver based wireless system, which is ideal for many BAN applications.**

Keywords – BAN, spectrum sensing, super-regenerative receiver, successive approximation register, ultra low power.

I. INTRODUCTION

Body area network (BAN) is a wireless network used for communication among sensor nodes operating on, in or around the human body in order to monitor vital body parameters and movements [1] [2]. A typical sensor node in BAN should ensure accurate sensing of the signal from the body, carry out low-level processing of the sensor signal, and wirelessly transmit the processed signal to a local processing unit.

One of the key challenges for successful realization of BAN is that the total energy consumption of the sensor should be drastically reduced to allow energy autonomy. This is especially important for implantable sensors. The power budget of the sensor could be further analyzed by individually examining the sensor's consisting blocks, e.g. energy supply, wireless communication, digital signal processing, sensing and read-out. In most of the cases, the wireless communication is a major power consumer in the sensor node of BAN [3].

A potential candidate to achieve ultra low power wireless communication in BAN is the super-regenerative receiver [4][5]. However, the main limitation of the super-regenerative receiver is the difficulty in choosing quench waveform to achieve optimum performance, and its relatively poor performance in the presence of interference because of the embedded envelop detector. On the other hand, the reliability of BAN needs to be paid special attention since an undetected life critical signal could lead to fatal consequences. To minimize the gap between the BAN application requirements and the super-regenerative receiver's technology limitations, in this paper, we propose an automatic algorithm to calibrate the optimal quench waveform, and employ spectrum sensing such that the system could automatically choose the correct channel to avoid data transmission in the presence of unacceptable interferences. Furthermore, we implement the algorithms on hardware and demonstrate their effectiveness by providing measurement results. These results show that our proposed autonomously operating super-regenerative receiver is very suitable for BAN.

This paper is organized as follows: in Section II, the principle of super-regenerative receiver and its blocks are discussed. Section III contains the method to achieve the autonomous operation of the super-regenerative receiver by proposing a method for automatic quench waveform calibration. Section IV discusses the energy based spectrum sensing. The performance results in terms of probability of mis-detection and probability of false alarm are presented in Section V. Finally the paper is concluded in Section VI.

II. SUPER-REGENERATIVE RECEIVER

A. Architecture

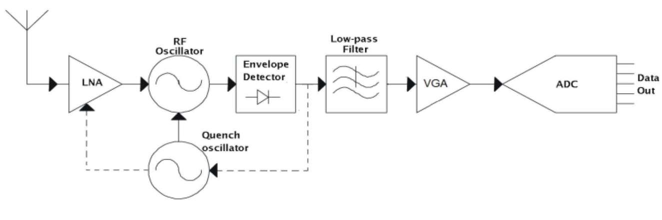

Figure 1. Architecture of the super-regenerative receiver.

As shown in Fig. 1, the main block of the super-regenerative receiver is the radio frequency (RF) oscillator which periodically starts up and shuts off oscillation controlled by a quench oscillator. The startup time of the RF oscillator is exponentially dependent on the magnitude of the input signal and could thus detect the presence of the signal.

B. *Quench waveform*

The performance of the super-regenerative receiver in terms of selectivity and sensitivity is determined by the quench current waveform generated from the quench oscillator. The performance behavior is analyzed under a sinusoidal, square, triangular and saw-tooth quench wave in [6]. The conclusion is that a saw-tooth waveform provides better selectivity. In [7], the selectivity is further enhanced by operating the oscillator first in the Q-enhancement mode, and after that in the amplification mode. The quench waveform is generated in a combined analog (ANA) and digital (DAC) fashion so that the super-regenerative receiver achieves both low power consumption and reasonable sensitivity and selectivity results.

As shown in Fig. 2, the optimal quench current waveform (I_{quench}) generated by the quench waveform generator (QWG) in [8] uses the "dig_clk_qch" clock to control the duty cycle of the DAC current, $I_{DAC.}$ This I_{DAC} level is adjusted by setting the number of bits and adjusting the referent current. The ANA of the waveform is designed such that a slow rising waveform is generated. Its duty cycle is controlled by the "an_clk_qch" clock. The final quench waveform is generated by superimposing the analog waveform on top of the DAC current. The $I_{critical}$ is the minimum bias current level at which the RF oscillator starts oscillating. The selectivity is improved by maintaining the oscillator first in the Q-enhancemnet mode ($I_{quench} < I_{critical}$) and after that in the amplification mode ($I_{quench} > I_{critical}$) [8].

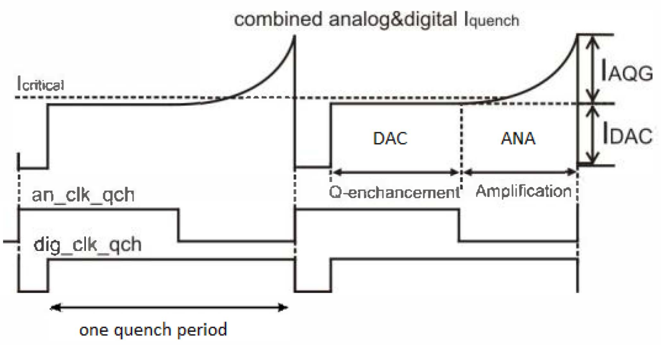

Figure 2. Optimum quench waveform [8].

III. AUTOMATIC QUENCH WAVEFORM CALIBRATION

In [8], we showed that a good calibration of the quench waveform parameters (DAC and ANA) can enable decent performance results for the ultra-low power super-regenerative receiver. In this section, we show the method of how these parameters could be calibrated. The main advantage of this proposed method is that the calibration input signal is not required. Therefore, it is different from the calibration method discussed in [7] where the input signal is required, and thus more suitable for automatic calibration. For simplicity of illustration, we use the 5-bit DAC and the 3-bit ANA values to define the quench current waveform. It could be easily extended to other DAC and ANA bit values.

The ideal DAC level (I_{DAC}) controlled by 5-bit DAC is determined such that it lies just below the critical current ($I_{critical}$) where the maximum selectivity can be achieved. As only I_{DAC} controls the $I_{critical}$ level, the ANA part of the QWG is switched off for the search of the DAC level. The optimal analog slope search is performed once I_{DAC} has been determined. This two-step search process is achieved using the successive approximation register (SAR) algorithm [7].

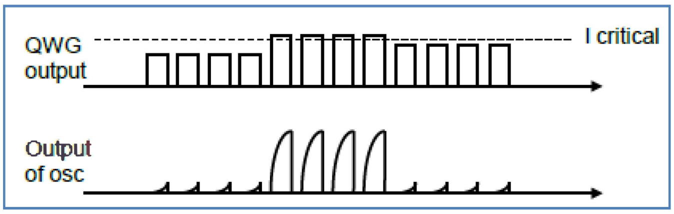

Figure 3. Concept of DAC level search.

The concept of determining the ideal DAC level is shown in Fig. 3. The QWG output will only be oscillated if the DAC level is higher than the $I_{critical}$ (critical current) level. So, this suitable level of DAC can be obtained by estimating a predetermined threshold that is calculated from the output of the analog to digital converter (ADC). This threshold level is found to be just below the $I_{critical}$ level indicating the point of highest selectivity. During this process, the parameter (ANA) controlling the analog slope is preferred to be switched off because only the DAC output level of the QWG controls the $I_{critical}$ level.

The proposed SAR algorithm based DAC level search is shown in Fig. 4. The DAC level is initially set to the middle value (decimal value 16 or binary value "10000") and then the estimated output power is compared with the pre-determined threshold. Based on the presence and absence of the oscillations, the DAC level is adjusted lower or higher respectively, by halving the value to its either extreme. This process is repeated until an ideal level just below the threshold is obtained, where the selectivity is at its best.

Following the above procedure is the determination of the optimum value for the analog slope. Considering the trade off between the "self oscillations" and "highest sensitivity" that occurs at very high analog slope angles, the highest slope is not preferred for this quench waveform. The analog slope search algorithm is similar to the DAC level search algorithm, however here we set the analog slope parameter higher or lower based on the comparison between the estimated output of ADC and the threshold value.

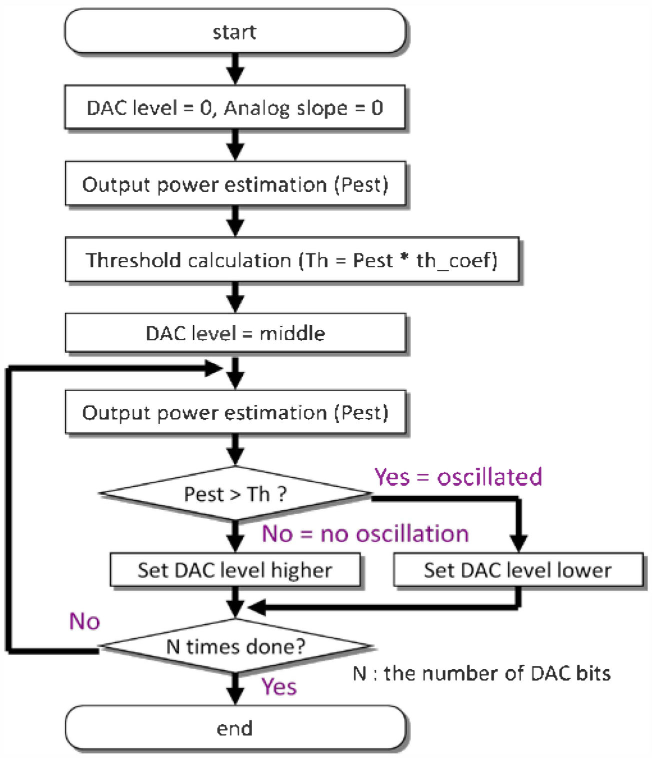

Figure 4. DAC level search based on SAR algorithm

Once both QWG parameters have been automatically calibrated, the spectrum sensing algorithm to be discussed in the next section is applicable such that the super-regenerative receiver can be automatically adapted to the transimission scheme depending on the presence of interference.

IV. Energy Detection Based Spectrum Sensing

Spectrum sensing is performed to ensure that the super-regenerative receiver based wireless system does not suffer strong interference during transmission. This is very important because of the relatively poor performance of the super-regenerative receiver in the presence of interferences. To minimize power consumption of the wireless system, energy detection (ED) based spectrum sensing is adopted. The detection is performed by comparing the output of the energy detector with the pre-determined threshold. The challenge lies in determining the ideal threshold, where the interference can be detected.

To understand more about the ED based spectrum sensing, consider the following received signal representation:

$$y(n) = s(n) + w(n) \quad (1)$$

where $s(n)$ is the detected signal, $w(n)$ is the noise and n is the sample index. The energy detector output can be written as

$$M = \sum_{n=0}^{N} |y(n)|^2 \quad (2)$$

where N is the size of the observation vector. The occupancy of the channel is determined based on the comparison between M and the fixed threshold λ_E. This threshold is optimally chosen in order to maximize the performance of the system. In this paper we have focused on two performance parameters of the super-regenerative receiver, namely probability of mis-detection (P_{MIS}) and probability of false alarm (P_F). If we define the signal received in the considered channel as the interference, the following hypotheses can be defined with respect to interference, based on the two probabilities mentioned above:

Let H_0 denote the absence of interference in the channel. We then have two conditions:

- H_{01}: Interference detected signifying a false alarm
- H_{00}: Interference not detected indicating a correct detection

Let H_1 denote the presence of interference in the channel. We thus have two conditions:

- H_{11} : Interference detected indicating a correct detection
- H_{10} : Interference not detected signifying a mis-detection

P_{MIS} is the probability that the test fails to detect the presence of interference in the channel. Thus a low probability is desired. It can be expressed as

$$P_{MIS} = Pr\,(M < \lambda_E / H_1) \quad (3)$$

P_F is the probability that the test incorrectly detects the presence of interference in the channel when it is actually not. It is clear that probability of false alarm should be kept as low as possible to ensure the maximum utilization of spectrum. The probability can be expressed as

$$P_F = Pr\,(M > \lambda_E / H_0) \quad (4)$$

V. Measurement Results

In this section, we provide the measured spectrum sensing results of a quench waveform calibrated super-regenerative receiver. In the measurement, the chip described in [8] is adopted as the hardware of the super-regenerative receiver. Its operation is controlled by the MSP430 microcontroller in which the quench waveform calibration and spectrum sensing algorithms are implemented. The single tone interference is generated by a signal generator. The probabilities of false alarm and mis-detection are determined for a number of frequency channels between 2.36 GHz and 2.46 GHz with a channel spacing of 10 MHz. The threshold is pre-determined by averaging the ADC outputs at a given interference power level. 1000 tests are carried out for each measurement point. Thus the results below 0.1% can only be displayed as 0.

A. Probability of false alarm

Fig. 5 represents the plot containing the probability of false alarm for a number of frequency channels. The pre-determined threshold value λ_E is calculated at three interference power levels (i.e. -75 dBm, -80 dBm, and -85 dBm). It can be observed that at higher power levels where the thresholds of the channels are higher, the performance is better compared to the performance at lower thresholds as expected. Furthermore, setting the threshold at -85 dBm interference power results in a false alarm below 1%, which is sufficient for most of BAN applications.

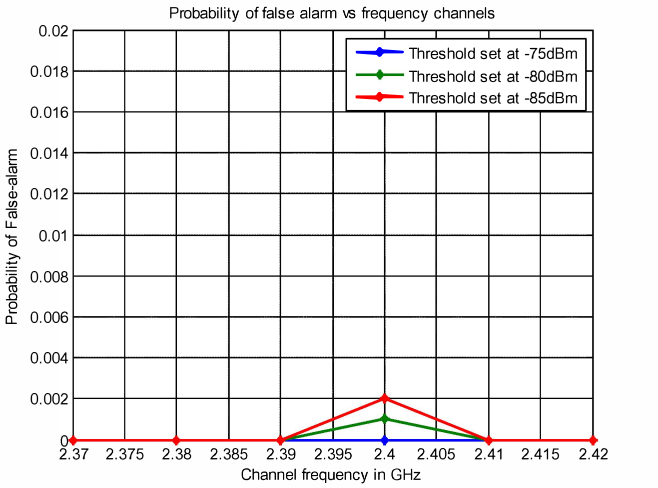

Figure 5. Probabity of false alarm for various frequency channels at different threholds

B. *Probability of mis-detection*

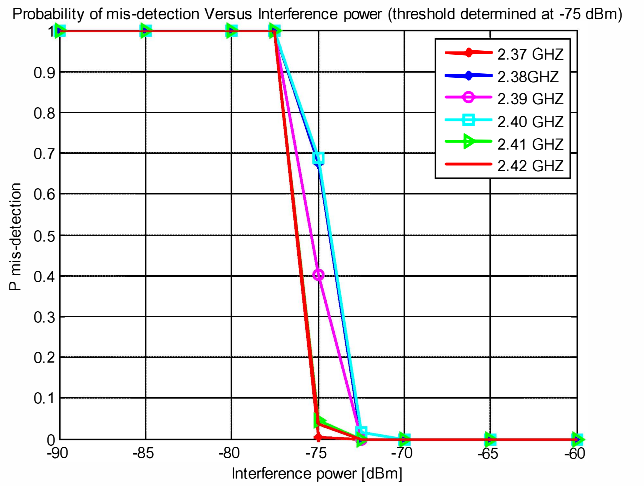

Figure 6. Probabiity of mis-detection versus interference power level for various channel threshold determined at -75dBm.

Fig. 6 shows the plots of P_{MIS} for various frequency channels at different interference power levels. The threshold λ_E is pre-determined from the ADC outputs, at -75 dBm interference power level. As expected, the performance is better at higher interference power levels. Furthermore, for all the channels considered, we find that when the interference power is 2.5 dB higher than the nominal interference power set for the threshold, the miss-detection probability is below 1%. Although not shown, similar conclusions could be drawn when the threshold is set at -80 dBm and -85 dBm interference power levels. Therefore, if we know the system's tolerance on the co-channel interference, we can pre-determine a threshold such that the mis-detection could be kept below 1%.

VI. Conclusions

In this paper we discussed the methods to achieve autonomous operation of the super-regenerative receiver, including the automatic quench waveform calibration to achieve optimal selectivity and sensitivity, and the energy detection based spectrum sensing to detect the presence of interference. The performance in terms of probability of mis-detection and probability of false alarm are measured for a number of frequency channels in the 2.36-2.46GHz band at various interference power levels. Our results show that, by using the automatic quench waveform calibration proposed in this paper, the spectrum sensing results do not change significantly over different channels. These stable results could facilitate the preset of a good threshold in spectrum sensing. Moreover, our proposed autonomously operating super-regenerative receiver can thus allow the wider use of the super-regenerative receiver in BAN applications.

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