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System Analysis of a Wake-Up Receiver Based on Surface Acoustic Wave Correlator

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Abstract- **This paper demonstrates system level analysis of an energy efficient Radio Frequency (RF) receiver. The receiver is based on a Surface Acoustic Wave (SAW) correlator which is used for highly linear demodulation and interferer suppression in conjunction with envelope detection for ultra-low power dissipation and hardware efficiency. The receiver is to be used in Wireless Sensor Networks (WSN) as a Wake-up Receiver (WuR) to reduce the network nodes power dissipation and provide asynchronous data communication. Low latency and high interference robustness makes this scheme interesting for industrial real-time applications. In this paper, the SAW correlator transfer function is derived, which functions as a Matched Filter (MF). Since the receiver uses envelope detection and based on the characteristic of the SAW, the receiver sensitivity is analyzed by means of a non-linear approach.**

I. INTRODUCTION

WSN nodes sense, process, and transmit data by means of wireless communication. The communication process with either the base station or with other nodes consumes considerable amount of power, where power efficiency represents one of the major challenges in the design of WSN nodes. As shown in Fig. 1, a typical WSN is built from distributed autonomous sensors nodes and a base station. If the base station coordinates the communication and a WuR is added to every node, the communication becomes asynchronous, real-time and on-demand which reduces the power dissipation significantly [1].

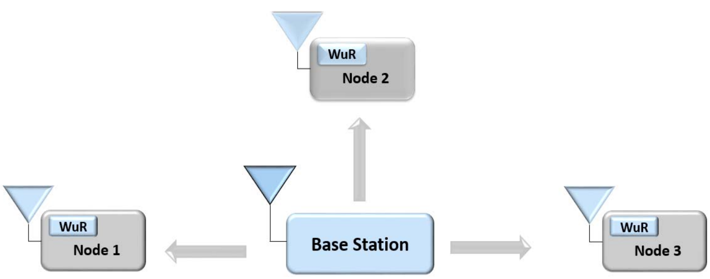

Fig. 1: WSN nodes with WuR

Low-power dissipation minimizes the maintenance effort for periodic battery replacement or in the optimal case provides unlimited operation by means of energy harvesting. The WuR continuously monitors the communication channel, listening for a wake-up signal transmitted by other nodes or by the base station. The node is only activated if and only if a wake-up signal is detected and the transmitted node ID matches the ID of the node. If the always-on WuR is designed with ultra-low-power dissipation, then the total WSN can be very energy efficient. Currently, most WuRs use envelope detection which allows for very hardware- and power-efficient receiver architectures. However wireless receivers using envelope detection are sensitive to co-channel interference which severely degrades the reliability of the WSN. Therefore WuR must not only be power-efficient but also robust to co-channel interference. Usually co-channel interference robustness is achieved by means of a heterodyne or homodyne receiver architecture and narrow-band filtering which however requires highly linear RF amplifiers and mixers as well as a local oscillator which leads to high power dissipation. Fig. 2 shows the system blocks of the proposed communication link which allows for high co-channel robustness and low power dissipation. The base station uses Linear Frequency Modulation (LFM) at a frequency of 2.4 GHz with a bandwidth of 80 MHz [8]. In the receiver, an SAW correlator is used to demodulate the received LFM signal while suppressing other wireless signals. Subsequently a WuR Integrated Circuit (IC) detects and amplifies the correlator output signal. It then compares it with the unique node ID and asserts the node's wake-up signal or not. Since the SAW-based demodulation operates completely passive, it is very power-efficient. Furthermore due to the compression gain, the WuR IC can be implemented using an envelope detector with low circuit complexity and power dissipation while still operating robustly in the presence of RF interferers [2].

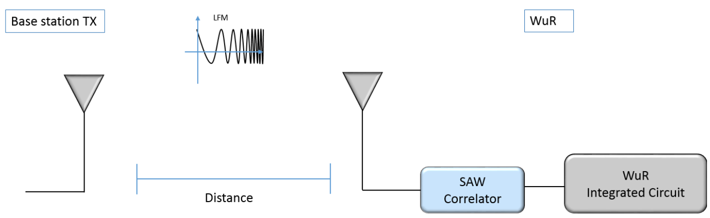

Fig. 2: Proposed communication system block

II. SAW CORRELATOR

A. Transfer Function and Peak SNR

The SAW correlator output signal is mathematically equivalent to the convolution between the received signal $r(t)$ and the correlator impulse response $h(t)$ as expressed in Eq. 1. The received signal is composed of the desired signal $x(t)$ and input noise signal $n_{in}(t)$. If the received signal matches with the correlator impulse response, the result of the correlation process is a compressed RF pulse.

$$r(t) * h(t) = x(t) * h(t) + n_{in}(t) * h(t) \tag{1}$$

The derivation of the correlator impulse response $h(t)$ starts from the definition of the instantaneous Signal to Noise Ratio (SNR) [3], which defines the level of the desired signal to the level of the noise combined with the signal. The instantaneous SNR is defined in terms of instantaneous power and noise as expressed in Eq. 2.

$$SNR(t) = \frac{P_{signal}(t)}{P_{noise}(t)} \tag{2}$$

For a correlator with a delay of t_d, the time domain output is a compressed RF peak whereby the peak voltage is reached at time t_d . Hence $SNR(t_d)$ is the maximum SNR and $t = t_d$ represents the optimal decision time. As given in Eq. 1, the SAW correlator output is the convolution between the received signal $r(t)$ and the correlator impulse response $h(t)$. The impulse response $h(t)$ must be designed in such a way that SNR(t_d) is maximized. For a linear system and based on Eq. 1, let

$$\begin{aligned} y(t) &= x(t) * h(t) \\ n_{out}(t) &= n_{in}(t) * h(t) \end{aligned} \tag{3}$$

where $y(t)$ refers to the output signal components and $n_{out}(t)$ refers to the output noise components. Based on Eq. 2, the output peak SNR is expressed by

$$SNR_{peak} = \frac{|y(t_d)|^2}{\overline{|n_{out}(t)|^2}} \tag{4}$$

where $|y(t_d)|^2$ is the output signal peak power and $\overline{|n_{out}(t)|^2}$ is the average power of the output noise. Using inverse Fourier transform and the properties of convolution theory in the frequency domain Eq. 4 is expressed as below, where $X(\omega)$ and $S_{in}(\omega)$ are the desired signal and input noise spectrum in frequency domain.

$$\frac{|y(t_d)|^2}{\overline{|n_{out}(t)|^2}} = \frac{\left|\frac{1}{2\pi}\int_{-\infty}^{+\infty} X(\omega)H(\omega)e^{j\omega t_d}d\omega\right|^2}{\frac{1}{2\pi}\int_{-\infty}^{+\infty} S_{in}(\omega)\,|H(\omega)|^2 d\omega} \tag{5}$$

The objective is to drive a transfer function $H(\omega)$ or impulse response $h(t)$ that maximizes the output SNR of the SAW correlator. To do this, Schwartz inequality is used. Refer to [3] for complete details of Schwartz theorem and derivation of SAW correlator output SNR. As given in Eq. 6 if two complex functions $f(t)$ and $g(t)$ are integrable over a closed period [a, b] then

$$\left|\int_a^b f(x)g(x)dx\right|^2 \leq \int_a^b |f(x)|^2 \int_a^b |g(x)|^2 \tag{6}$$

The inequality is only valid if the two functions can be written as $g(t) = Kf(t)^*$

$$f(x) = \left[\frac{X(\omega)}{\sqrt{S_{in}(\omega)}}\right] \tag{7}$$

$$g(x) = \sqrt{S_{in}(\omega)}H(\omega)e^{j\omega t_d}$$

Substituting Schwartz inequality in Eq. 7 into Eq. 6 gives

$$\frac{|y(t_d)|^2}{\overline{|n_{out}(t)|^2}} \leq \frac{\frac{1}{2\pi}\int_{-\infty}^{+\infty}\left|\frac{X(\omega)}{\sqrt{S_{in}(\omega)}}\right|^2 \left|\frac{1}{2\pi}\int_{-\infty}^{+\infty}\sqrt{S_{in}(\omega)}H(\omega)e^{j\omega t_d}d\omega\right|^2}{\frac{1}{2\pi}\int_{-\infty}^{+\infty} S_{in}(\omega)\,|H(\omega)|^2 d\omega} \tag{8}$$

The term on the right side of the numerator cancels with the denominator term as expressed in Eq. 9.

$$\frac{|y(t_d)|^2}{\overline{|n_{out}(t)|^2}} \leq \frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{|X(\omega)|^2}{S_{in}(\omega)} \tag{9}$$

From Schwartz inequality for equal terms, where $g(t) = Kf(t)^*$, the transfer function can be written as in Eq. 10.

$$\sqrt{S_{in}(\omega)}H(\omega)e^{j\omega t_d} = K\left[\frac{X(\omega)}{\sqrt{S_{in}(\omega)}}\right]^* \tag{10}$$

The optimal SAW correlator transfer function is expressed as $H(\omega) = X^*(\omega)e^{-j\omega t_d}$ and the corresponding impulse response can be expressed in Eq. 11.

$$h(t) = x^*(-t + t_d) \tag{11}$$

Hence the correlator impulse response is the conjugate of time-reversed version of the received signal $x(t)$, the SAW correlator behaves like a Matched Filter (MF), which functions as a signal compressor resulting in an increase of the SNR [5], [6].

Taking the input noise $S_{in}(\omega)$ as an Additive White Gaussian Noise (AWGN) and substitute $S_{in}(\omega) = n_{in,0}/2$ which represents the two-sided spectral density in Eq. 5, gives $|y(t_d)|^2 = E_x^2$ and $\overline{|n_o(t)|^2} = \frac{n_{in,0}}{2}E_x$ where E_x is the output signal energy. Based on above, the MF peak SNR is defined in Eq. 12 [3].

$$SNR_{peak} = \frac{2E_x}{n_{in,0}} \qquad (12)$$

B. LFM Pulse Compression

Pulse compression is the process of producing a narrow pulse with a high peak power from a long duration low power signal. The SAW correlator functions as a pulse compressor. Taking the LFM signal as the input signal to the SAW correlator, the output is a compressed pulse which ideally has the same energy as the input LFM signal as shown in Fig. 4.

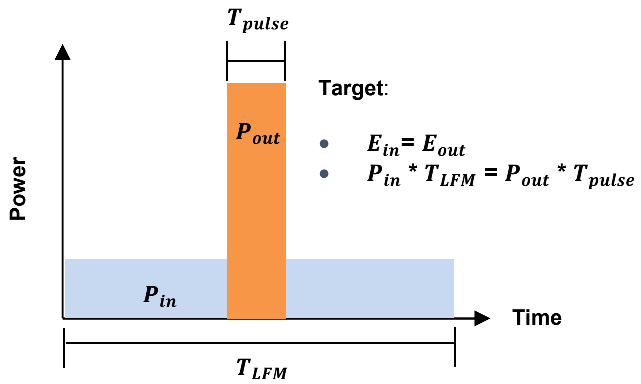

Fig. 4: LFM Pulse compression

The ideal power compression gain (without power losses) can be expressed as $A_p = BW_{RF} * T_{LFM}$ [5], [6], where BW_{RF} is the LFM signal bandwidth and T_{LFM} is the wavetime. Taking the input noise as AWGN as in Eq. 11 and assume the input signal energy E_{in} equals to output signal energy E_{out}, the Peak SNR can be rewritten as below:

$$SNR_{peak} = \frac{2 * P_{in} * T_{LFM}}{n_{in,0}} \qquad (13)$$

Given that the input power noise $n_{in} = n_{in,0} * BW_{RF}$, then Peak SNR equals to Eq. 14.

$$SNR_{peak} = SNR_{in} * 2\, BW_{RF} * T_{LFM} \qquad (14)$$

From Eq. 14 the peak SNR is a function of the SAW correlator power compression gain, which reflects on the receiver sensitivity performance discussed in next section.

III. RECIVER SENSITIVITY

Fig. 5 shows the complete target receiver architecture. Since the SAW correlator is a linear device, the impact of the SAW correlator output noise to the next stage is lumped into Insertion Losses (IL). The SAW correlator is followed by RF enveloped detector which is a non-linear device that demodulates the RF signal by squaring. The output noise of the envelope detector is composed from two sources, the signal-to-noise mixing and the noise-to-noise mixing. Eq. 15 and Eq. 16 show respectively the noise power $n^2{}_{ED,in}$ and signal power $x^2{}_{ED,in}$ at the input of the envelope detector (output of the SAW correlator) [7].

$$n^2{}_{ED,in} = kT * IL * BW_{RF} \qquad (15)$$

$$x^2{}_{ED,in} = P_{in} * A_p \qquad (16)$$

Where k is Boltzmann constant, T is ambient temperature, and kT is the thermal noise floor. IL refers to the device insertion losses, where usually the Piezoelectric material exhibit high insertion losses. A_p is the effective power compression gain which equals to the ideal compression gain divided by the device insertion losses as expressed in Eq. 17 [5], [6].

$$A_p = (BW_{RF} * T_{LFM} \,/\, IL) \qquad (17)$$

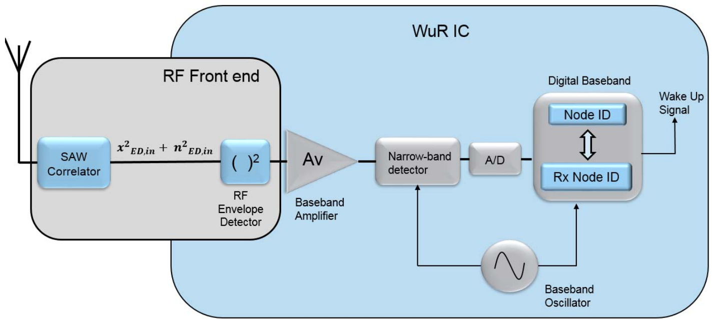

Fig. 5: Target WuR architecture

Assuming noiseless squaring device and neglecting the baseband amplifier noise contribution, the SNR_{out} at the output of the envelope detector is expressed in Eq. 18 [7].

$$SNR_{out} = \frac{x^4{}_{ED,in}}{8x^2{}_{ED,in} * n^2{}_{ED,in} + 4n^4{}_{ED,in}} \frac{BW_{RF}}{BW_{BB}} \qquad (18)$$

Substitute Eq. 15 and Eq.16 in Eq. 18 and solve the quadratic equation for P_{in}, the receiver sensitivity is defined in Eq. 19. Where BW_{RF} and BW_{BB} refere to RF bandwdith and baseband bandwith respectivlty. $SNR_{(out)min}$ is the minumum detectable SNR by the receiver at a certain Bit Error Rate (BER).

$$P_{sens} = \frac{4KT * SNR_{(out)min} * IL * BW_{BB}}{A_p} + \frac{2 * KT * IL * \sqrt{4BW^2{}_{BB} SNR^2{}_{(out)min} + BW_{RF}\, BW_{BB}\, SNR_{(out)min}}}{A_p} \qquad (19)$$

The envelope detector is followed by a basedband amplifer and a narrow-band detector which imrpoves the receiver sensitivty. After the RF pulse is detected and amplified to the proper digial level, a dicision circuit compares the node ID with the received ID and asserts the node's wake-up signal or not.

Based on Eq. 19, assume the $BW_{RF} = BW_{BB}$ = 80 MHz (from 2.4 – 2.480 GHz) and wavetime $T_{LFM} = 1.25\mu s$. Table I summrized the receiver sensitivity for several SAW correlator effective power compression gain as given in Eq. 17. The $SNR_{(out)min}$ = 12.5 dB, the maximum allowed transmitted power at 2.4 GHz is 20 dBm [8], and the receiver and transmitter antenna gain is 0 dBi.

Table I: Receiver sensitivity for several compression gain

A_p	5	2	1	0.5	0.25	0.1
P_{sens} (dBm)	-67	-59	-53	-47	-41	-33
Range (m)	230	90	45	22	12	5

The receiver sensitivity can be imporved by reducing the BW_{BB} from broadband detection to narrow band detection as shown in Fig. 5 . Taking BW_{BB} = 1 MHz and keep the other parameters as before, an improved receiver sensitivty is calculated in Table II.

Table II: Receiver sensitivity with narrow band detection

A_p	5	2	1	0.5	0.25	0.1
P_{sens} (dBm)	-85	-77	-71	-65	-59	-51
Range (m)	1800	700	350	180	90	35

IV. CONCLUSION

The use of SAW correlator along with the RF envelope detection and narrow-band detection represents an efficient WuR frontend architecture. It avoids the use of high power dissipation components such RF amplifiers, mixers and local oscillators. The SAW correlator functions as a MF which compresses the received signal while suppressing noise and interferers. Hence RF envelope detection can be used instead of coherent detection which allows for demodulation with very low power dissipation. By means of non-linear receiver sensitivity analysis, range and receiver sensitivity are calculated taking into account SAW correlator compression gain and insertion loss as well as baseband RF and baseband bandwidth. For realistic SAW compression gain and insertion loss, a baseband bandwidth of around 1 MHz allows for sensitivity of better than -85 dBm.

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