A DIRECT-SEQUENCE SPREAD-SPECTRUM SUPER-REGENERATIVE RECEIVER

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ABSTRACT

Current applications of the super-regenerative receiver use narrowband modulations. In this paper a new architecture that allows incoherent detection of spread-spectrum signals is presented. A pseudorandom code generator has been added to the original circuit. It is clocked by the quench oscillator and takes advantage of the characteristic broad reception bandwidth. CDMA can be achieved via ASK and FSK modulated signals with high simplicity in the RF stage as well as low power consumption.

1. INTRODUCTION

Since the super-regenerative receiver was presented by Armstrong in the early 1920's, it has been included in a variety of applications. Currently, it is a circuit widely used in low-range RF links (remote control systems, short-distance telemetry, etc). The reasons that make this receiver suitable for those applications are well known: simplicity, reduced cost and low power consumption. Additionally, it is able to demodulate both AM and FM and exhibits automatic gain control in the logarithmic mode [1]. Super-regeneration is suitable at high frequencies, where other types of receivers tend to be more complicated [2]. It has also been applied to infrared communications [3]. Recently, an integrated low-voltage low-power super-regenerative receiver has been proposed for ISM applications [4].

On the other hand, spread-spectrum systems offer certain desirable characteristics that are difficult to obtain by conventional techniques, such as an improved multipath resistance and the ability to coexist with other systems. Some radio-based wireless local area networks (WLAN's) make use of spread-spectrum techniques in ISM bands to allow flexibility and minimize interference [6]. Other advantages of spread-spectrum systems include: interference and jamming resistance, low spectral power density with low probability of intercept and code division multiple access (CDMA) capability.

When applied to narrowband communications, the super-regenerative receiver presents a major drawback: an excessive reception bandwidth which makes the receiver more sensitive to noise and interference compared to other systems. The circuit presented in this paper takes advantage of this property to detect certain types of spread-spectrum signals. A previous experiment was carried out by the authors controlling the quench signal with a pseudorandom code generator (*PN quench*) [5]. In the present work, the PN code generator is included in a new architecture that makes more efficient use of the incoming signal. The circuit combines the inherent advantages of the receiver with those of spread-spectrum systems.

2. BASIC OPERATION THEORY

A block diagram of the super-regenerative receiver can be seen in Fig. 1. The RF oscillator is controlled by a low-frequency quench oscillator that causes the RF oscillations to rise and die out repeatedly. An isolation amplifier is usually included to avoid re-radiation through the antenna. The signal generated in the oscillator is composed of a series of RF pulses separated by the quench period T_q. The periodic build-up of the oscillations is determined by the incoming signal $v(t)$, usually amplitude modulated according to

$$v(t) = V(t)\cos\omega_0 t = \frac{V_0}{2}\left[1 + x(t)\right]\cos\omega_0 t \qquad |x(t)| \le 1 . \tag{1}$$

In the linear mode, the oscillations are damped before they reach their limiting equilibrium amplitude, and its peak amplitude is proportional to the amplitude of the injected signal $V(t)$. If the quench oscillator originates the oscillations to start growing at t=0, then the voltage generated in the oscillator during the following quench period is [1]

$$v_{osc}(t) = V(0)S(\omega_0)K(t)\cos\omega_{osc} t \tag{2}$$

where $V(t)$ is supposed to be constant around t=0, $S(\omega_0)$ is the bandpass frequency response factor, $K(t)$ is an amplification function that includes regenerative and super-regenerative gains and ω_{osc} is the natural frequency of the oscillator. $K(t)$ provides the shape of the envelope of a single RF pulse. Both $S(\omega_0)$ and

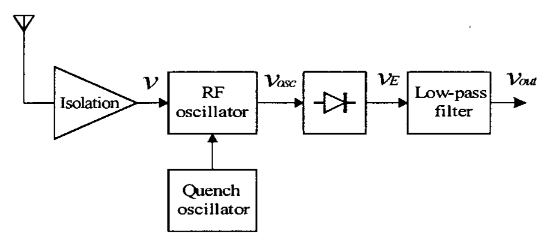

Figure 1. Block diagram of a conventional super-regenerative receiver.

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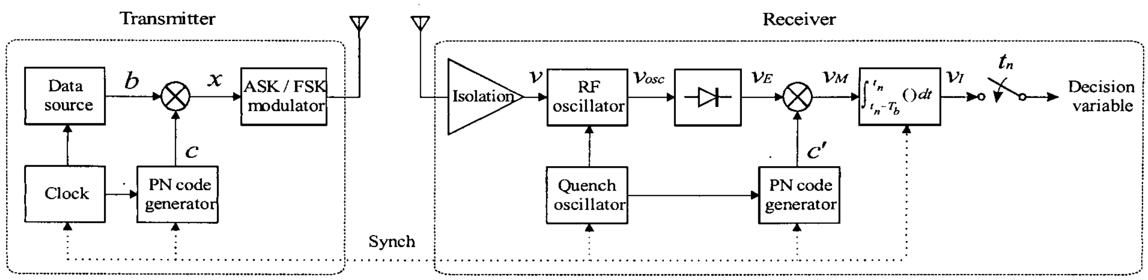

Figure 2. Block diagram of the transmitter and the spread-spectrum super-regenerative receiver.

$K(t)$ depend on the quench waveshape. When the residual signal from the previous quench cycle (*hangover*) is negligible in comparison with the incoming signal, the envelope of the oscillations can be expressed for all t by superposition of single quench interval responses,

$$v_E(t) = \sum_{m=-\infty}^{\infty} V(mT_q)S(\omega_0)K(t - mT_q), \qquad (3)$$

expression that emphasizes the behaviour of the receiver as a sampling device.

In the logarithmic mode the amplitude of the oscillations is allowed to reach its limiting equilibrium value. In this mode of operation the amplitude of the RF pulses remains constant, but the incremental area under the envelope is proportional to the logarithm of the amplitude $V(t)$. In both modes of operation, the modulating input signal may be retrieved by detecting the envelope of the oscillations and by low-pass filtering the quench components (Fig. 1).

3. SPREAD-SPECTRUM SIGNAL DETECTION

The following study supposes that the receiver operates in the linear mode and that the noise level is negligible. The focus is set on the ability of the receiver to detect certain kinds of spread-spectrum signals. Results are extensible to logarithmic mode.

3.1 Detection of ASK modulations

In direct-sequence spread-spectrum systems a digital binary PN sequence or code $c(t)$ having a chip rate of $f_c=1/T_c$ chip/s is multiplied by the digital binary baseband information $b(t)$ [7]. If $f_b=1/T_b$ is the bit rate, then the ratio $L=f_c/f_b$ gives the number of generated chips per bit. The signals $c(t)$ and $b(t)$ are considered to exhibit the two states +1 and −1, representing the logical values 1 and 0 respectively. The resulting spread-spectrum signal is

$$x(t) = c(t)b(t) \qquad (4)$$

In the system implemented the transmitter uses $x(t)$ as an ASK modulating signal (equation (1)), giving a bandpass on-off-keying (OOK) modulated signal that also has a spread spectrum. In order to extract the information from $v(t)$ a modified architecture of the receiver is proposed. The block diagram is shown in Fig. 2. The receiver incorporates a local PN code generator that uses the quench oscillator as a clock, so that the chip period is just the quench period, $T_c=T_q$. For each quench cycle a new chip value is obtained. The generated PN sequence $c'(t)$ is then multiplied by the envelope of the RF pulses prior to an integrate & dump processing. For proper operation, the two codes $c(t)$ and $c'(t)$ must be synchronized. Synchronism may be sent through an adjacent radio channel (synchronous operation) or retrieved from the spread-spectrum signal itself (asynchronous operation).

Under these conditions, and assuming that the receiver is tuned to the received frequency ($\omega_{osc}=\omega_0$, $S(\omega_{osc})=1$), the output of the multiplier is

$$\begin{aligned} v_M(t) &= c'(t)\sum_{m=-\infty}^{\infty} V(mT_c)K(t - mT_c) \\ &= \frac{V_0}{2}c'(t)\sum_{m=-\infty}^{\infty}[1 + c(mT_c)b(mT_c)]K(t - mT_c). \end{aligned} \qquad (5)$$

Since $c'(t)$ is constant during the chip period, it is possible to define $c'_m=c'(mT_c+\varepsilon)$ ($0<\varepsilon<T_c$). Let us assume that the n-th bit is being received at the instant mT_c. Then, naming $b_n=b(mT_c)$, $c_m=c(mT_c)$, equation (5) can be rewritten as

$$\begin{aligned} v_M(t) &= \frac{V_0}{2}\sum_{m=-\infty}^{\infty} c'_m(1 + c_m b_n)K(t - mT_c) \\ &= \frac{V_0}{2}\sum_{m=-\infty}^{\infty}(c'_m + c_m c'_m b_n)K(t - mT_c) \end{aligned} \qquad (6)$$

where b_n can be obtained by integrating $v_M(t)$ in the related bit period. The optimum sampling instant t_n is the end of that period. The output of the integrator is

$$v_I(t_n) = \int_{t_n-T_b}^{t_n} v_M(t)\,dt = \frac{V_0\overline{K(t)}T_c}{2}(\rho_{c'} + \rho_{cc'}b_n) \qquad (7)$$

where

$$\rho_{c'} = \sum_{m=0}^{L-1} c'_m , \quad \rho_{cc'} = \sum_{m=0}^{L-1} c_m c'_m . \tag{8}$$

The code balance $\rho_{c'}$ provides a constant offset while $\rho_{cc'}$ is a cross-correlation factor. If transmitter and receiver codes are equal, then $c_m c'_m = c_m^2 = 1$ and $\rho_{cc'} = \rho_{cc} = L$, giving

$$v(t_n) = \frac{V_0 \overline{K(t)} T_c}{2} (\rho_c + L b_n) . \tag{9}$$

However, if the two codes are different and exhibit a low cross-correlation (an interference is received), the output tends to be insensitive to $b(t)$. Therefore, the receiver introduces a processing gain upon the desired signal in relation to the interference equal to

$$G_p = \frac{L}{\rho_{cc'}} . \tag{10}$$

Fig. 3 shows an example of the implicated signals using a maximal-length sequence (*m*-sequence) of 7 chips. When the receiver generates the transmitted code and is properly synchronized, all the pulse envelopes are multiplied by the same sign, giving a positive or negative net area in every bit period. On the other hand, when the receiver uses an orthogonal sequence (in this case the shifted sequence $c'_m = c_{m-1}$), the net area over the bit period is zero or near zero.

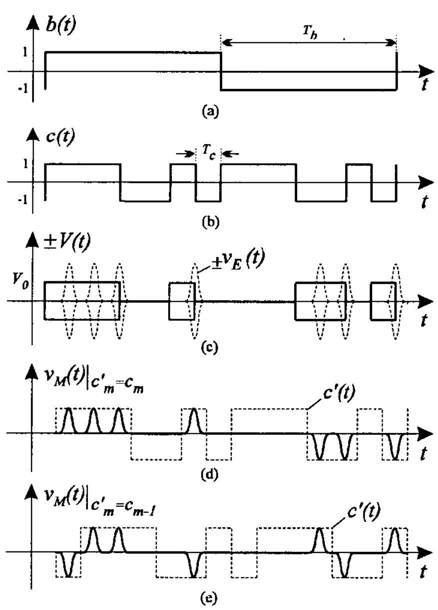

Figure 3. (a) Digital baseband information, (b) digital PN spreading *m*-sequence, (c) envelope of the received ASK signal and envelope of the RF pulses in the oscillator. Output of the multiplier: (d) with matching codes, (e) with orthogonal codes.

Previous results can be extended to the case of a transmitter and several receivers where the modulating signal is made by superposition of N spread-spectrum signals generated with orthogonal codes $c_i(t)$,

$$x(t) = \frac{1}{N} \sum_{i=1}^{N} c_i(t) b_i(t) . \tag{11}$$

The receiver owing the code $c_k(t)$ will be able to detect the data $b_k(t)$, remaining insensitive to signals coded with other sequences. Hence, N available channels share at once the same RF bandwidth, and separation is made by code division (CDMA system).

3.2 Detection of FSK modulations

When the receiver is tuned so that the carrier of the signal matches one of the slopes of its selectivity curve, the receiver is able to demodulate FM. Indeed, let us assume that the received signal is FSK modulated by the spread spectrum signal $x(t)$ defined by equation (4),

$$v(t) = V_0 \cos(\omega_0 t + \omega_d \int_{-\infty}^{t} x(\tau) d\tau) . \tag{12}$$

The signal $v(t)$ is a continuous-phase FSK modulation having a frequency deviation ω_d and an instantaneous frequency

$$\omega_i(t) = \omega_0 + \omega_d \, x(t) . \tag{13}$$

When $v(t)$ is applied to the receiver, the amplitude of the pulses depends on the instantaneous frequency of the input at the instant when they start to rise, and the output of the envelope detector is

$$v_E(t) = \sum_{m=-\infty}^{\infty} V_0 S(\omega_i(mT_c)) K(t - mT_c) . \tag{14}$$

Defining

$$\begin{aligned} S_0 &= \frac{S(\omega_0 + \omega_d) + S(\omega_0 - \omega_d)}{2} \\ S_d &= \frac{S(\omega_0 + \omega_d) - S(\omega_0 - \omega_d)}{2} \end{aligned} \tag{15}$$

and considering the digital nature of $x(t)$, it is possible to write

$$S(\omega_i(t)) = S_0 + S_d x(t) . \tag{16}$$

Replacing equation (16) in equation (14) gives

$$\begin{aligned} v_E(t) &= \sum_{m=-\infty}^{\infty} V_0 [S_0 + S_d \, x(mT_c)] K(t - mT_c) \\ &= V_0 S_0 \sum_{m=-\infty}^{\infty} \left[1 + \frac{S_d}{S_0} x(mT_c) \right] K(t - mT_c) . \end{aligned} \tag{17}$$

This result reveals that the received FSK signal appears as an ASK at the output of the envelope detector and, therefore, it may be demodulated by the same procedure.

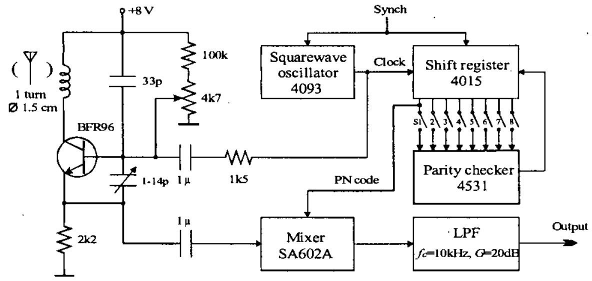

Figure 4. Partial schematic of the implemented receiver.

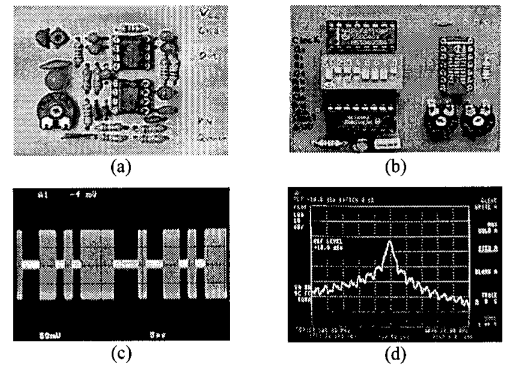

Figure 5. (a) RF oscillator, mixer and low-pass filter, (b) quench and PN code generators, (c) ASK input signal at 500 kchip/s and (d) its spectrum.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

A partial schematic of the implemented receiver is presented in Fig. 4. It is synchronous and works with *m*-sequences (synchronization circuit not shown). The RF oscillator and the envelope detector have been implemented with a Colpitts oscillator. The isolation amplifier has not been used. A squarewave oscillator generates the quench whereas a linear feedback shift register generates the PN code. An array of switches allows sequence selection and an active low-pass filter replaces the integrate & dump stage (this requires an increased bit period for short sequence-lengths).

Initial tests have been carried out by feeding the transmitter directly with the PN code generated in the receiver. The synchronism has also been sent via radio. Table I summarizes the available lengths and chip rates at 500 MHz carrier frequency (both ASK and FSK). The receiver exhibits a bandwidth closer to that of the incoming signal at higher chip rates. Minimum chip rate is limited by the first harmonic of the PN code, which appears at the filter output. Maximum chip rate is limited by hangover. For instance, 15 CDMA channels have been obtained for L=15. This results in an increased spectral efficiency in comparison with a conventional receiver taking 15 samples per bit (approx. the minimum required in practice to retrieve information from samples). The measured supply current at 500 kchip/s is 6 mA. Optimisation of the circuit can reduce this value. Currently, a prototype is being tested at 1.5 GHz, offering the possibility of applying higher chip rates.

Table I – Features (500 MHz carrier, f_b=10 kbit/s)

Parameter	MIN	MAX	
Sequence length, L	7	255	chip
Processing gain, G_p	17	48	dB
Chip rate, f_c	140	5000	kchip/s
3dB receiver bandwidth	2.7	15	MHz

5. CONCLUSIONS

This work reveals some potential capabilities of the super-regenerative receiver in spread-spectrum communications. A new architecture of the receiver uses PN sequences to obtain direct-sequence spread-spectrum signal detection. CDMA can be achieved. Because of the incoherent nature of the receiver, it is appropriate for ASK and FSK modulations. The receiver takes benefit of a high simplicity in the RF stage, low cost and low power consumption. At present, we are experimenting with PN code acquisition and tracking circuits to achieve asynchronous operation.

6. REFERENCES

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