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Paper

Effect of a root-raised-cosine filter on a BPSK stochastic resonance receiver

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Abstract: Signal filtering is necessary for wireless communication. However it causes the signal amplitude to fluctuate and affects the performance of stochastic resonance (SR) receivers. In this study, we evaluate the bit error rate (BER) performance of filtered binary phase-shift keying (BPSK) on an SR receiver. The results show that filtering improves the BER performance of the SR receiver because the amplitude fluctuation contributes to improving the SR effect. We also evaluate the effect of the roll-off factor, which determines the bandwidth of the filter and the amplitude fluctuation. The results demonstrate the applicability of the SR receiver to bandlimited BPSK signals.

Key Words: stochastic resonance, wireless communication, BPSK, bandlimit, root-raised-cosine filter, roll-off factor

1. Introduction

Stochastic resonance (SR) is a nonlinear phenomenon that can enhance the response of a system by adding noise under certain conditions [1]. In contrast to many other systems that deal with noise negatively, SR positively utilizes noise. A particular advantage of SR is that it can detect weak signals buried in noise.

The fundamental characteristic of this interesting phenomenon has been discussed in the context of nonlinear physics [2, 3], and the study of SR has spread to field such as neural systems [4, 5], human machine systems [6], nanotechnology [7], image processing [8, 9], electrical circuits [10, 11], and wireless communication.

This study focuses on the application of SR to wireless communication, examples of which have already been proposed. The expectations is that SR will be utilized for spectrum sensing in cognitive radio [12–14], detecting signals [15, 16], and improving receiver sensitivity [17–21].

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We focus on applying SR to a receiver in order to be able to communicate with weak signals. An SR-enabled receiver is likely to be more sensitive than a conventional one, allowing it to detect significantly weaker signals [18]. In previous research, an SR receiver in radio frequency (RF) was proposed [18] and implemented [19]. The SR receiver performed better with RF signals than it did with baseband ones [18].

However, the transmitted signal in these studies was not bandlimited. In a real situation, transmitted signals are necessarily bandlimited by a transmitter filter to remove spurious power and prevent interference with other channels. Filtering causes fluctuation of the signal amplitude, and fluctuating amplitude affects an SR receiver because the SR effect is highly dependent on the input signal amplitude.

In addition, we consider a parameter of the filter, namely the roll-off factor. This determines the filter bandwidth and amplitude fluctuation. A small roll-off factor leads to a stricter bandlimit and a larger amplitude fluctuation. However, if we set a very small roll-off factor, the communication quality is degraded because of inter symbol interference (ISI).

In this study, we evaluate the effect of a filtered signal on the SR receiver. We consider filtered and unfiltered signals with binary phase shift keying (BPSK) and evaluate the performance in relation to the bit error rate (BER). The results show that the performance of BPSK on the SR receiver is improved by filtering in the region where the noise power is lower than the optimal noise power of the SR.

This paper is organized as follows. First, we show the system model of an SR receiver with filtering in Section 2. In Section 3, we evaluate the BER performance of the SR receiver with and without filtering, and compare those results. Conclusions are given in Section 4.

2. System model

Figure 1 shows the system model of the SR receiver. We assume that the transmitted signal is filtered and that the received signal is too weak to be received by a conventional receiver, i.e., the received signal level is lower than the minimum one that the receiver can detect. Typically, we would use an SR receiver to receive such a weak (subthreshold) signal and communicate with it.

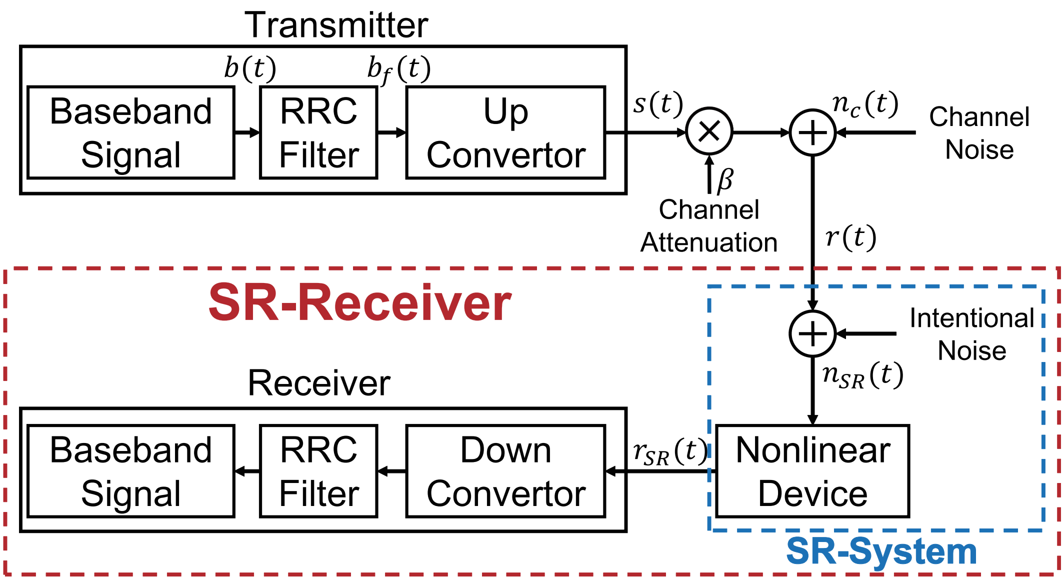


Fig. 1. System model of the SR receiver.

2.1 Transmitter

We assume that a BPSK signal is transmitted. The baseband $b(t)$ of this is given by

$$b(t) = \sum_i d_i g(t - iT), \tag{1}$$

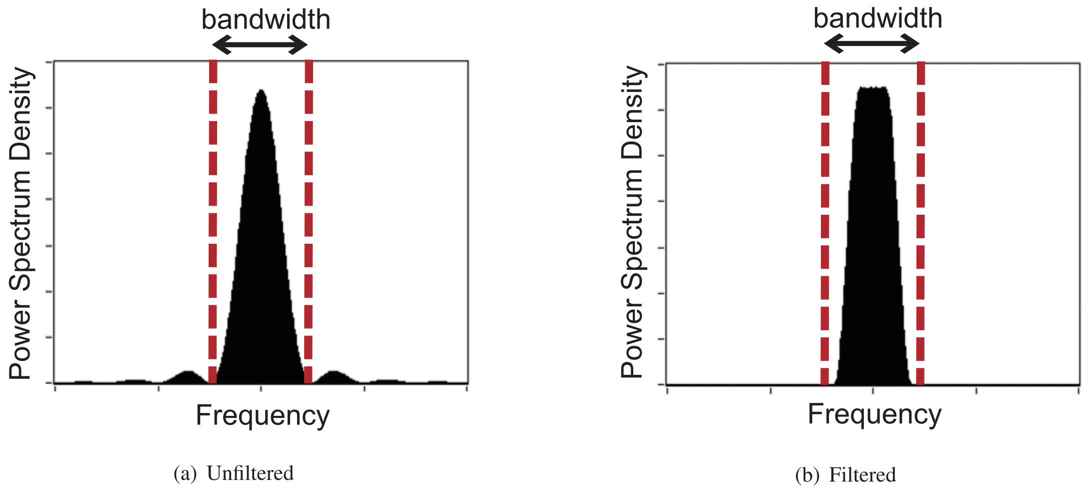


Fig. 2. Examples of the power spectrum density of BPSK signal with (a) no filtering and (b) filtering with an RRC filter ($\alpha = 0.5$).

where $d_i = \pm 1$ is the ith symbol of a binary data sequence, and $g(t)$ is a rectangular pulse of duration T and unit amplitude.

We denote $b_f(t)$ as the BPSK signal bandlimited by a root-raised-cosine (RRC) filter $x_{RRC}(t)$, given by

$$b_f(t) = x_{RRC}(t) * b(t), \tag{2}$$

where $*$ represents convolution. The frequency characteristic of $X_{RRC}$of $x_{RRC}(t)$ is given as

$$X_{RRC}(f) = \begin{cases} \sqrt{T} & 0 \le |f| \le \frac{1-\alpha}{2T} \\ \sqrt{\frac{T}{2}\left\{1 + \cos\left[\frac{\pi T}{\alpha}\left(|f| - \frac{1-\alpha}{2T}\right)\right]\right\}} & \frac{1-\alpha}{2T} \le |f| \le \frac{1+\alpha}{2T} \\ 0 & |f| > \frac{1+\alpha}{2T} \end{cases} \tag{3}$$

The Root-raised-cosine filters are commonly used in wireless communication systems because they help minimize ISI. The roll-off factor α determines the excess bandwidth of the signal. When $\alpha = 0.5$, the excess bandwidth is 50 %. A small roll-off factor results in strict bandlimiting but causes time-domain ripples and distortion. Therefore, in wireless communication systems, the roll-off factor is generally set to 0.2–0.5.

Figure 2 shows examples of a power spectrum density of a BPSK signal with (a) no filtering and (b) filtering with an RRC filter. The unfiltered signal illustrated in Fig. 2(a) has a spurious power spectrum. The filtered signal is bandlimited and without the spurious effects, as shown in Fig. 2(b).

After applying the RRC filter, $b_f(t)$ is upconverted to a carrier frequency f_c and the RF BPSK signal $s(t)$ is transmitted, which is given by

$$s(t) = b_f(t) \sin f_c t. \tag{4}$$

The transmitted signal $s(t)$ is propagated in a wireless communication channel. Through that channel, the transmitted signal is attenuated by factor β, and a channel noise $n_c(t)$ is added to the attenuated signal. In general, the latter is assumed to be a zero-mean Gaussian noise. The received signal $r(t)$ is given by

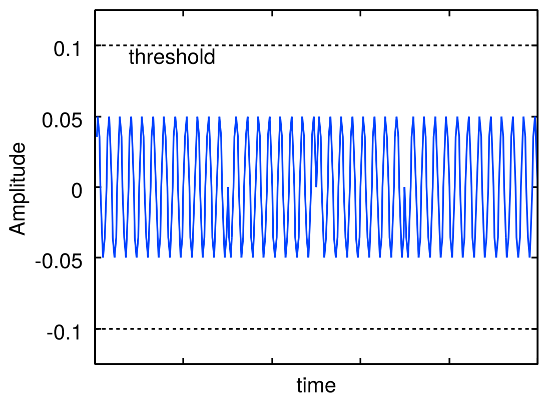
$$r(t) = \beta s(t) + n_c(t). \tag{5}$$

2.2 SR receiver

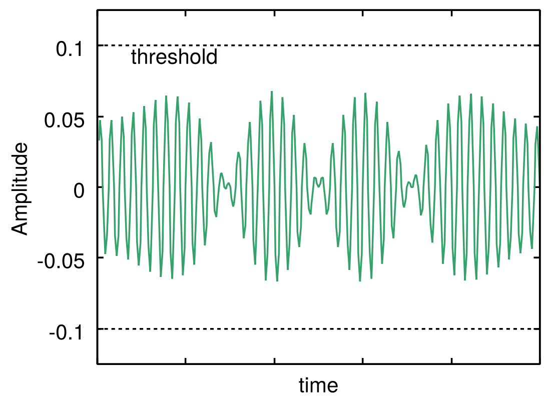
We construct an SR receiver comprising an SR system and a conventional RF receiver, as shown in Fig. 1, with the former connected to the front stage of latter.

We assume that the attenuated signal $\beta s(t)$ is lower than the minimum level ξ_{RX} that the receiver can detect, i.e.,

$$|\ \beta s(t)| < \xi_{RX}. \tag{6}$$



(a) Unfiltered



(b) Filtered

Fig. 3. Examples of the BPSK signal with (a) no filtering and (b) filtering with the RRC filter ($\alpha = 0.5$); (a) and (b) have the same power.

In this system, the received signal $r(t)$ is the input to the SR system. The SR system is composed of intentional noise n_{SR} and a nonlinear-device exhibiting SR. We use the SR system to enhance the received signal, after which the conventional receiver processes the output signal $r_{SR}(t)$ of the SR system. If the channel-noise power is too low for the SR system to perform optimally, we supply additional intentional noise n_{SR} and adjust the noise power to the optimal level of the SR [17, 19].

If the threshold of the SR system is less than or equal to the sensitivity of the conventional receiver, the performance of the former is likely to be better than that of the latter. This is because the SR receiver can detect subthreshold signals, unlike the conventional receiver.

The conventional receiver applies the RRC filter to baseband of the received signal. The receiver filter is the same as the transmitter one.

2.3 Filtering

In this section, we discuss how filtering affects the SR receiver.

Figure 3 shows examples of a BPSK signal in the time domain with (a) no filtering and (b) filtering with an RRC filter. In Fig. 3(a), the signal peak level is constant in its symbol duration. However, in Fig. 3(b), the peak level fluctuates significantly, which is caused by filtering and cutting the spurious power spectrum.

We focus on the fluctuation of the signal level caused by filtering. In the SR system, subthreshold signals can be detected by adding intentional noise to bring the signal peak level above the threshold. The performance of the SR system depends on the difference between the threshold and the amplitude, with a smaller difference yielding better SR performance. In this sense, the SR system is sensitive to the received signal level, and the fluctuation owing to filtering has some effect on its performance. Note that increasing α leads to larger fluctuations of the signal envelope.

In this study, we evaluate the effects of fluctuation by filtering. The SR performances with filtered and non-filtered signals are not identical because signal components with larger amplitudes are easier to detect than those of smaller amplitude. Therefore, the unevenness of the amplitude of the received signal may have some effect on the performance of the SR receiver.

3. Effect of filtering on BER performance

In this section, we evaluate the effect of a filtered BPSK signal on the SR receiver. We use filtered and unfiltered BPSK signals and evaluate the effect of filtering by comparing the results. First, we use the model shown in Fig. 1 and evaluate by simulation to show the effect of filtering. In this simulation, we use an SR receiver with a three-level device and one with a Schmitt trigger. Next, we confirm the effect of filtering experimentally by using RF signal and a software-define radio (SDR) receiver, which allows more practical choice of parameter values.

Table I. Parameter settings for simulation.

Parameter	Value
Threshold ξ_{SR}	100 [mV]
Modulation scheme	BPSK
Symbol rate $1/T$	100 [Hz]
Carrier frequency f_c	800 [Hz]
Transmitted data bits	10^5
Noise distribution	Gaussian
Noise bandwidth W_n	3.2 [kHz]
Sampling rate f_s	6.4 [kHz]
Filter type	RRC
Filter length	8
Roll-off factor α	0, 0.1, 0.2, 0.5

Table II. Signal amplitude parameter.

Roll-off factor α	0	0.1	0.2	0.5	unfiltered
Average amplitude [mV]	45.430	45.642	45.903	46.819	50
Maximum amplitude [mV]	108.1	103.4	93.5	73.0	50
Mean square amplitude [mV^2]	2.5	2.5	2.5	2.5	2.5

3.1 Numerical Simulation

3.1.1 SR receiver (three-level device)

In this simulation, we use the system shown in Fig. 1 and a three-level device as the nonlinear device, which corresponds well to the subthreshold-signal model. The three-level device has a threshold $\pm\, \xi_{SR}$ and exhibits good SR characteristics [21]. Its output $r_{SR}(t)$ is

$$r_{SR}(t) = \begin{cases} +V & r(t) + n_{SR}(t) > +\,\xi_{SR} \\ -V & r(t) + n_{SR}(t) < -\,\xi_{SR} \\ 0 & otherwise \end{cases} \tag{7}$$

The parameter settings for this simulation are listed in Tables I and II. The filter length determines the order of the finite-impulse-response filter. We set this parameter to a sufficiently large value for the simulation. We evaluate the BER performance of BPSK that is either unfiltered or bandlimited by the RRC filters, for roll-off factor α = 0, 0.1, 0.2, and 0.5. The roll-off factor α determines the filter bandwidth and the fluctuation amplitude. Table II lists the amplitudes of the received signals, which are all below the threshold of the three-level device. Both the filtered and unfiltered signals are given the same mean square amplitude, indicating that they also have the same signal power. In the the conventional receiver, if received signals are sufficiently large to be treated as linear, the BER performance of the BPSK signal depends on the signal power. This parameter setting of the amplitude ensures that the BPSK signals have the same BER performance with and without bandlimiting .

We also note that both the channel noise and the intentional noise are Gaussian.

Figure 4 shows the result of the simulation. The horizontal axis is the ratio of energy per bit E_b to noise power spectral density N_0 of the input of the three-level device, and the vertical axis is the BER performance of the SR receiver. As we see from the figure, the BER performance of the SR receiver improves in a specific noise-power region, which is typical of SR. In this region, the input noise power is optimal for SR, so the SR receiver detects a subthreshold signal and the BER performance is improved.

The optimal noise power is that which achieves the required BER. For example, as shown in Fig. 4, when the required BER is 10^{-2} and the signal is unfiltered, the range of optimal noise power is E_b/N_0 = 6∼13. In practically, we assume that the intentional use of an inexpensive and noisy device for SR, with the noise power roughly adjusted to bring it within the optimal range.

First, we compare unfiltered and RRC-filtered BPSK with α = 0.5. In the noisy region (E_b/N_0 <

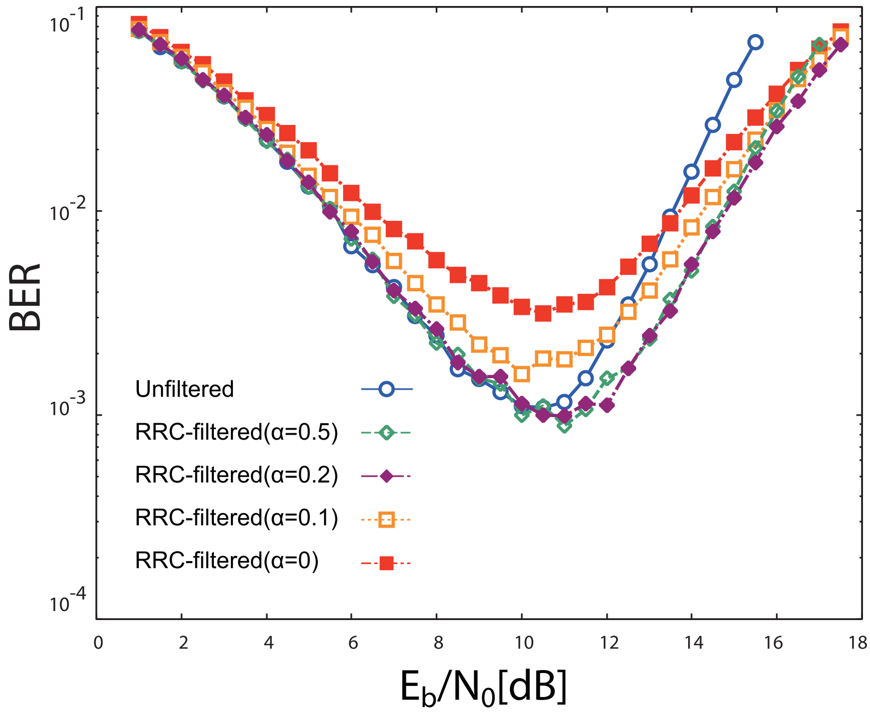


Fig. 4. Simulation results of BER performance of the SR receiver with the three-level device.

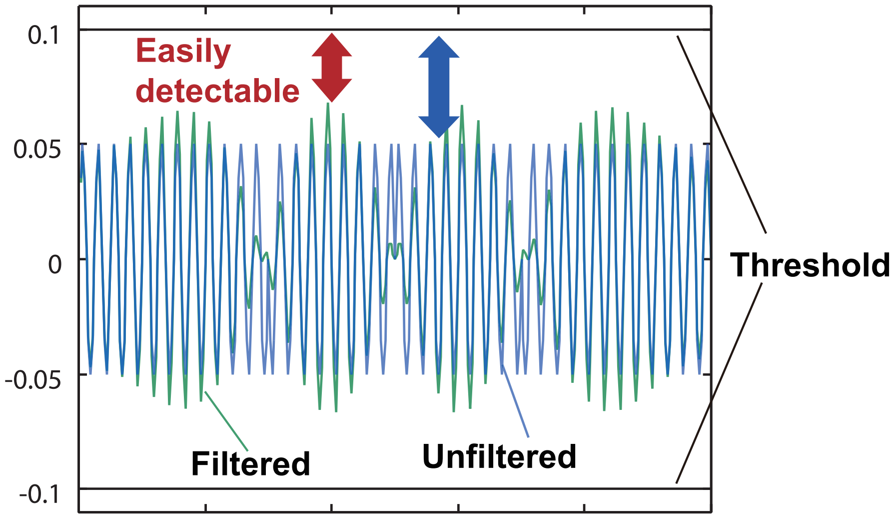


Fig. 5. Amplitude difference between BPSK signals with and without filtering. The green signal is the one shown in Fig. 3(a) expressing the unfiltered BPSK and the blue signal is the one shown in Fig. 3(b) expressing the filtered BPSK with the RRC filter ($\alpha = 0.5$). Note that no intentional noise is added.

10), unfiltered and RRC-filtered BPSK have the same BER performance as a conventional RF receiver without an SR system. However, in the region in which the noise power is lower than the optimal one of the SR ($E_b/N_0 > 12$), RRC-filtered BPSK exhibits better BER performance than does unfiltered BPSK.

The reason for this is the maximum amplitude. In an SR system, a subthreshold signal can be detected by adding noise so as to exceed the threshold. As Fig. 5 shows, fluctuations cause the amplitude of the filtered signal to approach the threshold. In the region in which the noise power is lower than the optimal one of the SR, the BER performance is diminished because a weak signal with low-power noise cannot exceed the threshold and hence cannot be detected. In an SR system, a suprathreshold signal is critical for detecting a weak signal. As Table II shows, the maximum amplitude of the filtered (RRC) BPSK signal is larger than that of the unfiltered one. When the

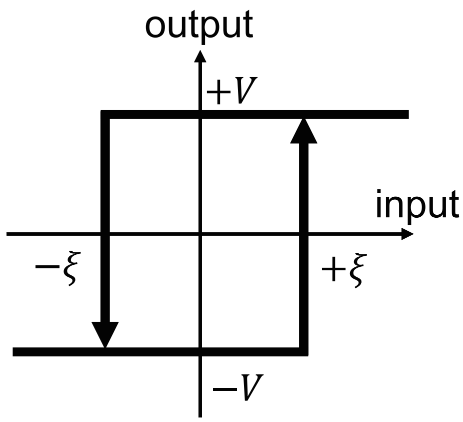


Fig. 6. Input-output characteristics of a Schmitt trigger.

noisy signal is mostly subthreshold, the signal amplitude difference contributes to signal detection by SR. The enhancement of signal by noise is stochastic, but the amplitude fluctuation by filtering is deterministic. Owing to its induced amplitude fluctuations, a filtered BPSK signal leads to better BER performance in the SR receiver than does an unfiltered one the same power. In the noisy region, the noise fluctuation is larger than the amplitude fluctuation by filtering, so filtering does not affects the BER performance.

However, the amplitude fluctuation is not the only factor that determines the BER performance of the SR receiver. As shown in Table II, a smaller roll-off factor (i.e., $\alpha = 0$ or 0.1), leads to a larger amplitude. However, as in a conventional receiver, this causes ISI. Therefore, in comparison with the results for unfiltered BPSK, the BER performance in noisy region is poorer for smaller roll-off factors because of ISI. However, in the noiseless region, a small roll-off factor leads to better BER performance because of the larger amplitude.

In conventional wireless communication systems, the roll-off factor is generally set to 0.2–0.5, which improves the BER performance of the SR receiver sufficiently in practice.

3.1.2 SR receiver (Schmitt trigger)

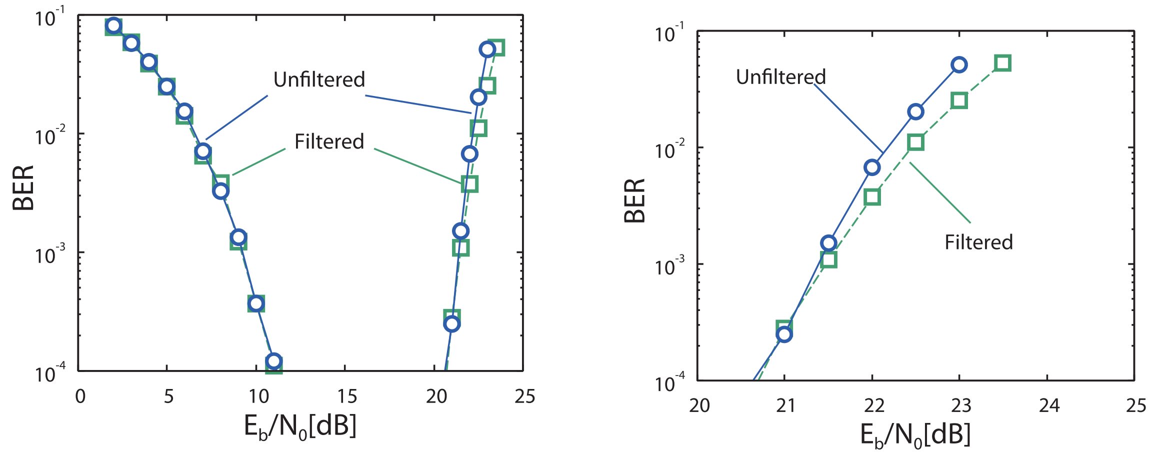
We can also use a Schmitt trigger as the nonlinear device in the SR receiver because of its well-known SR capabilities. In fact, a Schmitt trigger is the only device available to us experimentally; see Section 3.2. A Schmitt trigger has a dynamic threshold that depends on the state that it is currently in. Its input-output characteristics are shown in Fig. 6.

In this simulation, we compare the BER performances of unfiltered and RRC-filtered BPSK at $\alpha = 0.5$, which shows large performance improvement in the above simulations. We set a sampling rate $f_s = 51.2$kHz and a noise bandwidth $W_n = 25.6$kHz. In the SR system, the signal enhancement by noise occurs randomly. Therefore, the symbol decision in the SR receiver depends on the sampling rate f_s and the noise bandwidth W_n. By using large value of f_s and W_n, the correlation between the subthreshold signal and the output of the SR system is increased. The performance of the SR receiver with the Schmitt trigger is not as good as that with the three-level device [21]. To allow the performance of the BPSK signals with and without bandlimiting to be compared, larger values of f_s and W_n are used, enhancing the SR effect. The other parameters are set as is Tables I and II.

Figure 7 shows the results of the simulation. These have the same characteristics as those of the simulation with three-level device. Compared with Fig. 4, the difference in BER performance with and without filtering is smaller here. This is because of the different nonlinear SR devices. The improvement in BER performance by filtering is caused by the SR effect; thus, the degree of improvement should depend on the SR performance of the nonlinear device.

3.2 Experiment

In this section, we evaluate the effect of a filtered BPSK signal on the SR receiver in RF frequency experimentally. The results confirm that the performance of the SR receiver is improved by bandlim-



(a) BER performance of the SR receiver with the Schmitt trigger

(b) BER performance in a lower input noise power of (a)

Fig. 7. Simulation results of BER performance of the SR receiver with a Schmitt trigger (sampling rate $f_s = 51.2$kHz and noise bandwidh $W_n = 25.6$kHz): (a) full input–noise-power range; (b) expanded view of lower input-noise-power region.

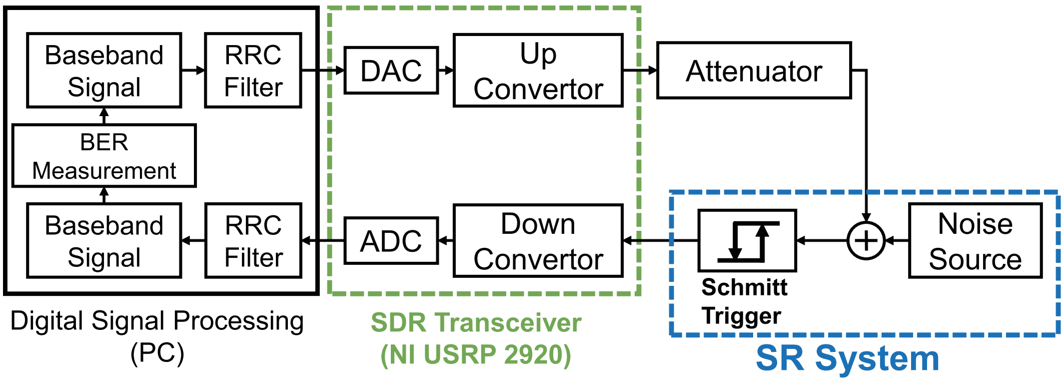


Fig. 8. System for measuring the BER of the SR receiver.

iting. A different system model and different parameters settings are used in the experiment and the simulations. In this experiment, we use the more practical system model and parameter settings for the carrier frequency, the symbol rate, and the method for sampling the signal.

The BER measurement system is shown in Fig. 8, and the parameter settings are listed in Tables III and IV. We use a Schmitt trigger as the nonlinear device and an SDR transceiver (NI USRP 2920) as the conventional transceiver. The baseband signals are filtered by digital signal processing. The threshold level of the Schmitt trigger ξ_{SR} is higher than that of the SDR receiver.

In contrast with the simulation, the carrier frequency is high and the symbol rate is sufficiently lower than the carrier frequency. Moreover the output of the SR system is sampled after downconverting, while the system model used in the simulation treated all sampling points as being in RF.

For SR at RF, the Schmitt trigger is designed with a high-speed comparator (Analog Devices ADCMP607) that has a wide input bandwidth of 750MHz [20]. The input noise, which is the sum of the channel and intentional noise, is assumed to be a zero-mean Gaussian noise. We add 100MHz-bandwidth noise using a vector signal generator (Agilent Technologies N5182A).

The transmitted signal is attenuated by an attenuator, and the signal with noise is fed into the Schmitt trigger. Table IV shows the amplitude of the received signals, which are subthreshold of the Schmitt trigger. We set the roll-off factor $\alpha = 0.5$, which is the practical value and shows good performance in the above simulation.

Figure 9(a) shows the BER performance of the SR receiver. The result shows SR phenomenon, the BER performance improves in a specific noise power.

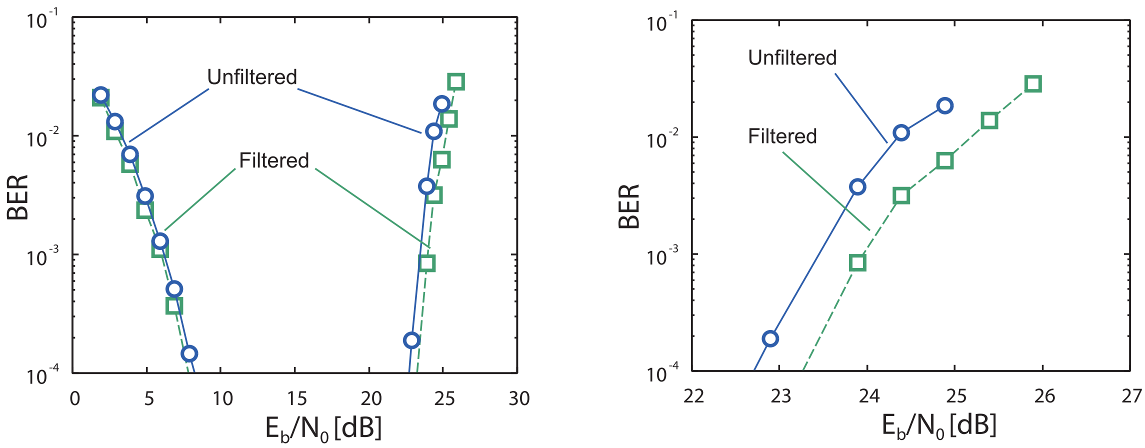
In this experiment, the BER performances show the same characteristics as those of the simulation

Table III. Parameter settings for BER measurements.

Parameter	Value
Threshold of Schmitt Trigger ξ_{SR}	100[mV]
Modulation scheme	BPSK
Symbol rate $1/T$	250[kHz]
Carrier frequency f_c	70[MHz]
Transmitted data bits	10000
Number of trials	100
Noise distribution	Gaussian
Noise bandwidth	100[MHz]
I/Q sampling rate	4[MHz]
Filter type	RRC
Filter length	8
Roll-off factor α	0.5

Table IV. Signal amplitude parameters.

Filter type	none	RRC
Average amplitude [mV]	35	32.78
Maximum amplitude [mV]	35	51.1
Mean square amplitude [mV^2]	1.225	1.225



(a) BER performance of the SR receiver

(b) BER performance in a lower input noise power of (a)

Fig. 9. Results of experimental BER measurements: (a) full input-noise-power range; (b) expanded view of lower input-noise-power region.

results. Figure 9(b) shows the results for noise powers lower than the optimal one for SR. In this region, the difference in BER performance between BPSK with and without filtering is significant, with RRC-filtered BPSK having better BER performance than unfiltered BPSK.

Note that the experimental performance was superior to that suggested by the simulation. This may be attributed the different system models and parameter settings used.

4. Conclusion

In this study, we evaluated the BER performance of filtered BPSK on an SR receiver by simulation and experiment. The results showed that filtering improved the BER performance of the SR receiver when the noise power was lower than the optimal one for SR. The reason for this was that amplitude fluctuations contributed to improving the SR effect, which appeared especially when the noisy signal is mostly subthreshold. By means of these results, we have demonstrated the applicability of an SR receiver to BPSK signals that are bandlimited by a practical filter.

Acknowledgments

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