A PVT-independent Schmitt trigger with fully adjustable hysteresis threshold voltages for low-power 1-bit digitization applications

Ke Lin, Xin’an Wang, Xing Zhang, Bo Wang, and Tingbing Ouyang

Abstract: This paper proposes a process, voltage, temperature (PVT) independent Schmitt trigger with fully adjustable hysteresis threshold voltages. These characteristics are attributed to the proposition of a self-tuning circuit in the inverter-comparator, along with a feedback controlling network for hysteresis characteristic. The proposed Schmitt trigger is designed and fabricated with SMIC 0.13 µm CMOS technology. It has much less power consumption of only 2.51 µW, and features also an adjustable hysteresis threshold voltages ranging from 350 mV to 850 mV at a minimum supply voltage of 1.0 V. All these advantages make it very suitable to work as 1-bit digitization in a low power sensing node.

Keywords: body area network, 1-bit digitizer, Schmitt trigger, PVT independence, adjustable hysteresis

Classification: Integrated circuits

References

1 Introduction

In body area networks [1], the Schmitt trigger is widely used in sensing nodes as a 1-bit digitizer to detect the weak signal [2]. It is also used to shape the disturbed signal [3] from sensors for pulse detection or pulse-width signal demodulation application.

One of the classic Schmitt triggers is based on an op-amp with three resistors to form a regenerative feedback [4]. It could easily control its hysteresis voltages by adjusting the resistors value in its feedback network. In addition, it could maintain the correct hysteresis voltages (determined by the resistors ratios) against process and temperature variation. However, its satisfying advantages are achieved by the high-gain property of the op-map, at the cost of consuming a relatively large static current [4], which is not acceptable in modern low power body area networks.

Another kind of commonly used Schmitt trigger and its modification are based on simple inverter-comparator, as reported in [5, 6, 7, 8, 9]. They operate with little static current and some could adjust the hysteresis voltages by pre-setting a DC bias voltage. But, they suffer unpredictable threshold voltage caused by PVT variations resulted from inverter-comparator based implementation, which limits their application as a low-error 1-bit digitizer in body area sensing nodes.

In this paper we propose a low power PVT-independent Schmitt trigger with fully adjustable hysteresis threshold-voltages for the sensing nodes in body area networks. We have introduced hysteresis characteristic through a feedback mechanism, and thus we have largely improved the PVT and the adjustability of the conventional inverter-comparator structure.

2 Inverter-comparator with PVT variation compensation

Now we briefly review the conventional inverter-comparators and existing methods of PVT variation compensation, and show their advantages and weakness.
In a low power 1-bit digitization application (such as pulse-width signal demodulation circuits or pulse detection circuits), the simple digital inverter (Fig. 1a) is one of the most effective approaches to realize the voltage comparator for converting the input analog signal to digital signal [5]. Despite the fact that the gain and slew rate is not limited by a bias current and that it provides the maximum possible charging and discharging current for a given supply voltage, it suffers unpredictable inherent threshold voltage caused by PVT variations [10], as shown in Fig. 1b.

\[ V_{\text{in}}(V) \]

\[ V_{\text{out}}(V) \]

**Fig. 1.** (a) A single CMOS inverter. (b) Unpredictable \( V_{T,\text{inv}} \) due to PVT variation

In order to make the threshold voltage of an inverter-comparator controllable and constant under any PVT condition, a self-tuning circuit [10] was introduced in the inverter-comparator circuit, as shown in Fig. 2a.

**Fig. 2.** (a) Inverter-comparator with self-tuning circuit. (b) Equivalent circuit structure

The PVT-independent inverter-comparator is comprised of a self-tuning circuit and a main-function circuit, and its equivalent circuit is shown in Fig. 2b. As can be seen from Fig. 2a, the self-tuning circuit is an inverter (\( M_{P1} \) and \( M_{N1} \)) connected to the supply rail through a PMOS and a NMOS (\( M_{P2} \) and \( M_{N2} \)). Its output (terminal \( V_{th} \)) is connected to the gates of \( M_{P2} / M_{N2} \), such that \( M_{P2} \) and \( M_{N2} \) are biased at the triode region. The main-function circuit are designed with the identical sizes as the...
self-tuning circuit. Similarly, the PMOS and NMOS (M_{P4} and M_{N4}) at the supply rail are also biased by \( V_B \). So, the inverter-comparator in the main-function circuit obtains the same inherent threshold as the one in the self-tuning circuit, which constantly equals to \( 1/2 \ V_{DD} \) against PVT variations and achieves the best noise margin [11]. However, this circuit lacks the hysteresis and adjustable threshold voltages, which are crucial to reduce the sensitivity to noise and disturbances in sensing nodes of body area network [5].

### 3 Schmitt trigger with fully adjustable hysteresis based on PVT-insensitive inverter-comparator

In this paper, we propose a novel Schmitt trigger. First, we introduce adjustable hysteresis to the inverter-comparator. This is achieved by a pair of complementary upper and lower threshold-voltage-tuning branches (enclosed by red and blue dash lines) through feedback controlling \( V_{ctrl} \) and \( \bar{V}_{ctrl} \), as shown in Fig. 3. By biasing the complementary threshold-voltage-tuning branches at adjustable voltages \( V_{BL} \) and \( V_{BH} \), the inverter-comparator is able to achieve voltage-controlled hysteresis characteristics, which realizes an adjustable Schmitt trigger. Second, we introduce PVT-compensation technique into the self-tuning circuits to maintain stable hysteresis voltages \( V_{TL} \) and \( V_{TH} \). In the following two subsections, we present respectively these two techniques.

![Proposed Schmitt trigger circuit with hysteresis threshold-voltage-tuning branches.](image)

**Fig. 3.** Proposed Schmitt trigger circuit with hysteresis threshold-voltage-tuning branches.

#### 3.1 Inverter-comparator based Schmitt trigger with complementary threshold-voltage-tuning branches

In order to realize hysteresis characteristic, two complementary upper and lower threshold-voltage-tuning branches are introduced to the main-function inverter-comparator (M_{P11} and M_{N11}). Each branch could set independently the lower or upper threshold voltages \( V_{TL} \) or \( V_{TH} \) of the main-function inverter-comparator.
When $V_{IN}$ is at the edge of falling or rising, a pair of complementary controlling signals ($V_{ctrl}$ and $V_{ctrl}$) are fed back to the switches to separately activate/deactivate the corresponding (lower and upper) threshold-voltage-tuning branches. Since the voltages of these two branches are biased by their self-tuning circuits with different DC bias voltage ($V_{bias, high}$ and $V_{bias, low}$), this realizes the adjustable threshold voltages for the main-function inverter-comparator. The equivalent circuit for generating $V_{TL}$ and $V_{TH}$ are shown in Fig. 4.

![Fig. 4.](image)

(a) Equivalent circuit when $V_{IN}$ is switching from high to low.  
(b) Equivalent circuit when $V_{IN}$ is switching from low to high.

Now consider a case when the input voltage $V_{IN}$ is at the edge of switching from high to low, at that moment the initial state of $V_{ctrl}$ is high and $V_{ctrl}$ is low. Following the feedback path of $V_{ctrl}$ and $V_{ctrl}$, the lower threshold-voltage-tuning branch is thus activated while the upper threshold-voltage-tuning branch is deactivated. So, the Schmitt trigger is equivalent to the circuit in Fig. 4(a). With $V_{IN}$ dropping across the threshold voltage set by lower threshold-voltage-tuning branch, $V_{OUT}$ switches from low to high immediately. Likewise, when $V_{IN}$ is switching from low to high, the upper threshold-voltage-tuning branch is activated and the other one is deactivated, as shown in Fig. 4(b). Only after $V_{IN}$ goes up across the threshold voltage set by it, $V_{OUT}$ will switch from high to low.

Hence, following the rising or falling edge, the proposed inverter-comparator could operate at different threshold voltages, thus working as a Schmitt trigger. Compared with the op-amp based Schmitt triggers, the proposed Schmitt trigger employs less transistors, thus occupies less chip area and consumes less power.

### 3.2 PVT variation compensation for fully adjustable $V_{TL}$ and $V_{TH}$

To ensure the robustness of the hysteresis under any PVT condition, we design a self-tuning circuit for each threshold-voltage-tuning branch, as shown in Fig. 4.

In a self-tuning circuit, $M_{P13, low}$ and $M_{N13, low}$ ($M_{P13, up}$ and $M_{N13, up}$) operate at the triode region, acting as two resistors inversely controlled by their gate-source voltages, with the same sizes as $M_{P33}$ and $M_{N33}$ ($M_{P23}$ and $M_{N23}$). The inherent threshold voltage $V_{T, self-tuning}$ of the self-tuning circuit could be written by:

$$V_{T, self-tuning} = \frac{(V_{ds,p} + m \cdot V_{ds,n}) + (V_{T_p} + m \cdot V_{T_n})}{1 + m}$$

$$= \frac{(m \cdot r_{ds,n} - r_{ds,p}) \cdot I + (V_{T_p} + m \cdot V_{T_n})}{1 + m}$$ (1)
where

\[
m = \sqrt{\frac{\beta_n}{\beta_p}} = \sqrt{\frac{\mu_p C_{ox} (W_n/W_p)}{\mu_p C_{ox} (W_n/W_p)}}
\]

\( I \) is the switching current of the inverter, \( r_{dc,p} \) and \( r_{dc,n} \) are the equivalent resistors, \( V_{TP} \) and \( V_{TN} \) are the threshold voltage, \( \mu_p \) and \( \mu_n \) are the carriers mobility of PMOSs and NMOSs, \( C_{ox} \) is the gate capacitance per unit area and \( W \) and \( L \) are the channel width and length of the devices.

The mechanism of anti-PVT variation is explained as follows. If the inherent threshold voltage \( V_{T,\text{self-tuning}} \) is below the DC bias voltage \( V_{bias,low} \) \( (V_{bias,high}) \), the output voltage \( V_{BL} \) \( (V_{BH}) \) of self-tuning circuit will drop below its inherent threshold voltage \( V_{T,\text{self-tuning}} \), leading to an increase of \( V_{gs,p13,low} \) \( (V_{gs,p13,up}) \) and a decrease of \( V_{gs,n13,low} \) \( (V_{gs,n13,up}) \). This will result in a smaller \( r_{dc,p} \) and a larger \( r_{dc,n} \), then pulls \( V_{T,\text{self-tuning}} \) higher, as can be seen from Eq. (1). Through the negative-feedback mechanism, \( V_{T,\text{self-tuning}} \) in the self-tuning circuit will approach its DC bias voltage \( V_{bias,low} \) \( (V_{bias,high}) \) eventually. On the contrary, if the inherent threshold voltage exceeds the DC bias voltage \( V_{bias,low} \) \( (V_{bias,high}) \) due to PVT variation, \( V_{T,\text{self-tuning}} \) will be pushed lower and lower through an inverse negative-feedback mechanism and eventually it approaches \( V_{bias,low} \) \( (V_{bias,high}) \) as well. Therefore, the equally biased transistors (with identical sizes) in the main-function circuit and the self-tuning circuits, the inherent threshold voltage in the main-function circuit \( V_{T,\text{main-function}} \) will simultaneously reach \( V_{bias,low} \) \( (V_{bias,high}) \) as well. Therefore, the main-function inverter-comparator with this activated threshold-voltage-tuning branch reliably maintains a PVT-independent threshold voltage \( V_{TL} \) \( (V_{TH}) \).

Moreover, because the lower and upper threshold-voltage \( V_{TL} \) and \( V_{TH} \) of the proposed Schmitt trigger are inherited from its corresponding self-tuning circuit, the \( V_{TH} \) and \( V_{TL} \) are fully adjustable by setting different \( V_{bias,high} \) and \( V_{bias,low} \).

4 Simulation and measurement results

Firstly, the proposed PVT-independent Schmitt trigger with fully adjustable hysteresis is designed and simulated in SMIC 0.13 µm CMOS technology. The simulation is performed under different PVT conditions with a combination of fast/slow MOSFET, high/low supply voltage and high/low temperature.

In order to verify the robustness of the circuit against the PVT variation, the DC transfer characteristics are simulated for its static performance. Simulation results in Fig. 5(a), Fig. 5(b) and Fig. 5(c) illustrate the accuracy of \( V_{TH} \) and \( V_{TL} \) in the proposed Schmitt trigger when process, temperature and supply voltage changes. The results show that the maximum variation of \( V_{TH} \) or \( V_{TL} \) is held within 2 mV under all situations when pre-set \( V_{TH} \) is 750 mV and \( V_{TL} \) is 450 mV. Besides, simulation results in Fig. 5(d) show that the \( V_{TH} \) and \( V_{TL} \) could be fully adjusted by \( V_{bias,high} \) and \( V_{bias,low} \), ranging from 650 mV to 850 mV and from 550 mV to 350 mV with a fine step of 50 mV.

Secondly, we designed and fabricated a wideband-signal receiver chip (Fig. 6) for human body communication, in which the proposed Schmitt trigger as 1-bit digitizer can be fully verified in real experiments. The measured results with die
photograph are given in Fig. 7. The transmitted signal (square wave), after the attenuation of human body channel, becomes the weak wideband pulse signal. It is then amplified by wideband preamplifier, and sent to the proposed Schmitt trigger. The latter acts as a 1-bit digitizer to quantizing the amplified wideband pulse signal. It shows that, the proposed Schmitt trigger has correctly recovered the transmitted square waveform at the fundamental frequency of 5 MHz.

![DC transfer characteristics](image1.png)  ![DC transfer characteristics](image2.png)

**Fig. 5.** DC transfer characteristics under different: (a) processes, (b) temperatures, (c) voltages and (b) pre-set DC bias voltages.

![Block diagram](image3.png)

**Fig. 6.** Block diagram of a wideband-signal receiver for human body communication

Finally, the performance comparison of the proposed approach with the previously reported works is summarized in Table I. The overall static current dissipation is 2.51 µA at a supply voltage of 1 V, far less than comparator based Schmitt trigger with a high-gain op-amp [4]. The proposed circuit can operate with
relatively higher speed in sensing nodes applications [2, 4, 9] of body area network. Moreover, it achieves precisely adjustable hysteresis against PVT variation while the previous Schmitt triggers based on modified inverter-comparator [9] or traditional Schmitt trigger [6] structure could not achieve.

5 Conclusion

A new PVT-independent Schmitt trigger with fully adjustable hysteresis threshold voltages is presented, and implemented using SMIC 0.13 µm CMOS technology. By introducing a self-tuning circuit in the inverter-comparator structure, this circuit could operate with nearly constant threshold voltages with large PVT variation: all

![Die photograph and measured results of the prototype wideband-signal receiver for human body communication. (a) Die photograph. (b) Low-jitter square waveforms recovered by the proposed Schmitt trigger communication](image)

**Table 1.** Performance comparison

<table>
<thead>
<tr>
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<th>[2]</th>
<th>[4]</th>
<th>[6]</th>
<th>[9]</th>
<th>This work</th>
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<tr>
<td>Consumed Current</td>
<td>3.4 µA</td>
<td>1.5 mA</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Supply Voltage</td>
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<td>1 V</td>
<td>3.3 V</td>
<td>2 V</td>
<td>1 V</td>
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<tr>
<td>Power Consumption</td>
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<td>1.5 mW</td>
<td>N/A</td>
<td>N/A</td>
<td>2.51 µW</td>
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<td>250 nm</td>
<td>130 nm</td>
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<td>130 nm</td>
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<tr>
<td>Signal Frequency</td>
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<td>2 MHz</td>
<td>133 MHz</td>
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<td>5 MHz</td>
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<td>Sensing Node</td>
<td>High Speed Buffer</td>
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<td>Structure</td>
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<td>Traditional Close Loop Comparator</td>
<td>Modified Traditional Schmitt Trigger</td>
<td>Inverter-Comparator based Schmitt trigger</td>
<td>Inverter-Comparator based Schmitt trigger</td>
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<td>Fixed</td>
<td>Adjustable</td>
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<td>PVT insensitive</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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process conditions, supply voltage ranging from 1.0 V to 1.4 V and temperature ranging from −40°C to 100°C. With adding feedback controlling network and presetting DC bias voltages, this circuit has a wide range adjustable hysteresis threshold voltages from 350 mV to 850 mV at a minimum supply voltage of 1.0 V. This proposed new Schmitt trigger enables the rejection of the disturbances caused by PVT variations, and is suitable for low power 1-bit digitization application in sensing nodes of body area networks.

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