Design and Implementation of a Socket with Low Standby Power

Cheng-Hung Tsai, Ying-Wen Bai, Hao-Yuan Wang and Ming-Bo Lin

Abstract — Turned-off electric home appliances generally still require standby power when they are plugged in. In this paper we present a way to reduce the standby power of a socket. Our socket supplies the appliances with power when the user turns them on. When the user turns them off, our socket shuts the electric power off and reduces the standby power to zero. Our design, which uses a microcontroller unit (MCU), receives signals from a pyroelectric infrared (PIR) sensor which detects the user approaching the socket. A power detector provides an MCU to control the solid state relay (SSR) On/Off when used as an appliance switch for shutting off the standby power. The components we use are very inexpensive and consume only 0.2 W. The MCU monitoring program provides both automatic detection of the user by the PIR sensor and detection of power consumption.

Index Terms — Electric Home Appliances, Standby Power, PIR, SSR, Power Consumption.

I. INTRODUCTION

That a device is switched off doesn’t mean that it is not consuming electric power. Many modern home appliances contain clocks, memories, remote controls, microprocessors and instant-on features that consume electricity whenever they are plugged in. And most appliances are plugged in 24 hours a day, 7 days a week. While such standby power often doesn’t amount to much, it really adds up [1]-[4]. Timers and remote controls in home appliances are for the convenience of the user. The built-in microcontroller is in standby state awaiting user commands while the appliances are either turned off or plugged in. The standby state power of the microcontroller is supplied by an adapter which has no power-off switch. The adapter as a power supply in the appliance converts AC 120 V into low voltage DC for the microcontroller [5]. The adapter, which is very inefficient at low power, consumes between 4 and 8 Watts or about 100 to 200 Watt-hours daily, which is not only many times the power actually used by the microcontroller but also enough to run a compact fluorescent light for about ten hours. On some appliances the on/off switch is placed on the secondary (low voltage side) of the supply’s transformer. The primary, which is not switched off, is always connected to the AC 120 V source. The inverter or commercial power grid views the primary of the transformer as a constant load. Power consumption of these devices may run into 50 to over 200 Watt-hours daily [6]. In the long run electronic devices in standby state, therefore, consume much power, usually ten percent of the electricity used in a home [7], [8].

In 2000 the International Energy Agency (IEA) proposed to reduce the standby power of electrical apparatus to less than 1 Watt within ten years [9]-[11]. It is imperative to develop new techniques to reduce the power consumption in electronic circuits. A recently published survey shows that various attempts have been made to reduce such power leakage to make the adapter more efficient [12]-[15]. Another way to improve efficiency is accurate control of the apparatus by both software and microcontroller [16]-[18].

In this paper we present a simple design to reduce the standby power of a socket. We call our design the “low standby power socket”. In our design the circuits consist of a few common components with low power consumption and low cost. This low standby power socket with its low amount of standby power can be used by existing appliances; this socket is easy to set up, it is cheap and it saves power more efficiently. Consequently, it is suitable for use in most home appliances.

The organization of this paper is as follows. In Section II we present circuit designs and a flowchart of the low standby power socket. In Section III we present the measurement of the power consumption of our design to verify the total power saved. In Section IV we show the mathematical equation for interpreting the low standby power socket. In Section V we draw the conclusions.

II. CIRCUIT DESIGNS OF THE LOW STANDBY POWER SOCKET

Most electric home appliances such as televisions, washing machines and microwave ovens are operated manually. The user turns an electric home appliance on to perform a specific function. Most control panels on electric home appliances are easy to operate. But even when using a remote control, the user must still be near the appliance in question to turn it off again. Thus home appliances could still be running whenever the user has left. If the user is not around the appliances, they are not being used and should always be in the turned-off state, so they won’t use any unnecessary standby power. To reduce the total amount of standby power used we present a simple design that detects the approaching user. When the user is detected by the PIR sensor used in our design,
the power for the electric home appliances is enabled. Conversely, if the PIR sensor doesn’t detect the user, the power is disabled as if the appliances were unplugged. If the appliances are working but the user leaves, the power continues to come from the socket until the work is finished. Because of this requirement we have designed the power detector circuit. The block diagram of the low standby power socket is shown in Fig. 1.

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**Fig. 1. Block diagram of the low standby power socket.**

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Fig. 1 shows how a microcontroller unit (MCU) controls the solid state relay (SSR) to supply the power for electric home appliances. The control mechanism is similar to that of an automatic power switch. The PIR sensor detects whether the user is approaching or not [8]. When the user approaches, the SSR1 supplies power to the appliances, and if there is no one nearby, the power stops. In order for the appliances to stay on after the user leaves, the SSR1 supplies power until the work is finished. Our software module shown in Fig. 2 detects whether an appliance is working and eliminates the possibility of the SSR1 turning the power off as the user leaves. The ultracapacitor, the SSR2 and the charger circuit are designed to reduce the power consumption of the AC/DC converter.

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**A. PIR circuit**

The PIR sensor detects whether the user is approaching or not in order to decide whether the SSR1 should supply power to the appliances. Fig. 3 shows the PIR circuit, where a PIR sensor is used as an electronic device to measure the infrared light radiating from objects or human bodies nearby. The PIR sensor detects motion and generates a voltage signal which is amplified, digitalized and sent to the MCU to judge whether a user is approaching.

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**B. Power detector circuit**

For the electric home appliances to stay on after the user leaves, the function must continue with power coming from the socket until the work is finished. We have designed the power detector circuit for this requirement [9], [10]. Fig. 4 shows this circuit in which we use a toroidal coil inductor as a current sensor that detects whether the appliance is working. When an AC current passes through an inductor, a small sinusoidal voltage $V$ is induced.

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$V$ is a small sinusoidal voltage induced by the toroidal coil inductor. $i(t)$ is an AC current in the AC power line.
\[ B = a \mu(t) \frac{\mu i(t)}{2\pi r} \] where \( r \) is the shortest distance from the wire to anywhere of the ring, and \( \mu \) is permeability.

To calculate magnetic flux \( \Phi \):
\[ \Phi = \oint B \cdot ds = \int_0^{2\pi} a \mu(t) \frac{\mu i(t)}{2\pi r} a_\theta zd\theta r = \mu i(t) \left( b^2 - \sqrt{d^2 - b^2} \right) \]  
(1)

where \( z = \sqrt{b^2 - (d + b - r)^2} \), \( b \) is the radius of the cross section of the toroidal coil inductor and \( d \) is the shortest distance from the wire.

\[ V = -N \frac{d}{dt} \Phi \]  
(2)

where \( N \) is turns of the wire.

Finally \( V = -N \mu \left( b^2 - \sqrt{d^2 - b^2} \right) \frac{d}{dt} i(t) = -L \frac{d}{dt} i(t) \)  
(3)

We represent the small sinusoidal voltage in the following general form.

\[ V = -L \frac{d}{dt} i(t) \cos(\omega t + \theta) \Rightarrow I_m \cos(\omega t + \theta) \]  
(4)

The phase angle \( \theta = -90^\circ \) could be omitted. In this circuit, as the phase response is not important, therefore the induced voltage \( V \) is written as

\[ V = \omega L I_m \cos(\omega t) \]  
(5)

where \( L = N \mu \left( b^2 - \sqrt{d^2 - b^2} \right) \) is the inductance of the toroidal coil inductor.

The amplitude of the induced voltage is proportional to the amplitude of the used current. This small induced voltage is amplified and converted into a DC signal by the diodes and capacitors and is then inputted to the MCU to determine whether the appliance is in the work state or not.

A voltage of more than 3 V is logic 1 and of less than 3 V is logic 0. We have measured the power detector circuit output voltage to the MCU with a DVD player and a microwave oven as AC load. The measurement result is shown in Fig. 5. When the AC load is in standby state, the power detector circuit output is 0 V and the power detector circuit output is 3.5 V. The reason why we chose a microwave oven and a DVD player as AC load is that a microwave oven is a high power home appliance and a DVD player is a low one. The power detector circuit works well with high and low power home appliances and also works well with other appliances.

The MCU receives signals from both the PIR and the power detector circuit and judges whether the user is approaching or a home appliance is working. The MCU controls the SSR1 that is supplying power to the appliances. When the MCU receives a signal that there is no user approaching or no home appliance working, the MCU causes the SSR1 to turn the power off to eliminate the standby power of the appliance.

When we measuring the power consumption of the low standby power socket without any home appliance load no matter whether the user is approaching or not, we find that the total power consumption of the socket is 0.4 W, which is less than the standby power of most electric home appliances.

Table I shows the breakdown of the power consumption of each module in our design, when the work voltage is 5V. Fig. 6 depicts the percentage of the power consumption of each module, with the user either approaching or not approaching.

<table>
<thead>
<tr>
<th>Module</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIR</td>
<td>5 V × 1 mA</td>
</tr>
<tr>
<td>Power Detector</td>
<td>5 V × 0.35 mA</td>
</tr>
<tr>
<td>Charger</td>
<td>5 V × 0.01 mA</td>
</tr>
<tr>
<td>MCU</td>
<td>5 V × 3.02 mA</td>
</tr>
<tr>
<td>AC/DC converter</td>
<td>500 mW</td>
</tr>
<tr>
<td>Total</td>
<td>521.9 mW</td>
</tr>
</tbody>
</table>

The measurement result is shown in Fig. 5. When the AC load is in standby state, the power detector circuit output is 0 V and the power detector circuit output is 3.5 V. The reason why we chose a microwave oven and a DVD player as AC load is that a microwave oven is a high power home appliance and a DVD player is a low one. The power detector circuit works well with high and low power home appliances and also works well with other appliances.

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**Fig. 5. Power detector circuit output with different AC loads.**
In Fig. 6 the power consumption of the AC/DC converter takes up to from 88.6\% to 95.9\% of the low standby power socket power consumption.

C. Charger circuit

The power from the AC/DC converter, which is more than the circuit actually needs, wastes a lot of power. To improve this problem we design a charger circuit. Fig. 7 shows the charger circuit design.

The ultracapacitor as a battery supports the whole circuit operation of the low standby power socket. The AC/DC converter’s DC output is the power source that provides the ultracapacitor with charge current when its voltage is lower than a predefined value. The SSR2 is set on the primary side of the AC/DC converter as a switch controlled by the MCU.

The lowest work voltage in our design is 3V. The breakdown voltage of the ultracapacitor is 2.5V. To increase the breakdown voltage there are two ultracapacitors connected in series. Thus in Fig. 7 the voltage of the two series ultracapacitors (V_C) is between 3V and 5V. Between these voltages all circuits operate normally.

When V_C is 5V, V_G1=3.52V, and MN1 turned on, I_{D1}=10 \mu A. V_G2=5V-500k \times 0A=3V ⇒ V_G2>V_{th}. MN2 is turned off, I_{D2}=5.6 \mu A. V_D2=3V-500k*5.6\mu A=0V. For the MCU V_{D2}=0V is logic 0.

The MCU receives the high logic that causes the SSR2 to turn off, the ultracapacitors to discharge and V_C to decrease.

When V_C decreases to 3V, V_G1=2.11V and MN1 is turned off, I_{D1}=0\mu A. V_G2=3V-500k \times 0A=3V ⇒ V_G2>V_{th}. MN2 is turned on, I_{D2}=5.6 \mu A. V_D2=3V-500k*5.6\mu A=0V. For the MCU V_{D2}=0V is logic 0.

The MCU can detect if V_C is below 3 V and causes the SSR2 to turn off so that the AC/DC converter charges the ultracapacitors, and V_C rises. After the AC/DC converter has charged the ultracapacitors for 95 secs, V_C reaches 5 V and the MCU causes the SSR2 to turn off, thus stopping the charge. The ultracapacitors’ charging time from 3 V to 5V is 95 secs. This value is known from measurements. The MCU keeps the hardware circuit from detecting that V_C is rising to 5V, we save both power consumption and cost. Fig. 8 shows V_C and power consumption with respect to charging and discharging time when no user approaches.

For the MCU V_{D2}=5 V is logic 1. The MCU receives the high logic that causes the SSR2 to turn off, the ultracapacitors to discharge and V_C to decrease.

In Fig. 8 the power consumption of the discharging time is 0 W and that of the charging time is more than 6 W when no user approaches. The charge and discharge of the ultracapacitor are a cycle whose time is \( T_{cycle} = T_{charge} + T_{discharge} \).

We denote the average power in \( T_{cycle} \) as \( P_{cycle} \) and

\[
P_{cycle} = \frac{\sum P_{charge} + \sum P_{discharge}}{T_{charge} + T_{discharge}}
\]  

(6)

where \( \sum P_{discharge} = 0 \) W

thus \( P_{cycle} = \frac{\sum P_{charge}}{T_{cycle}} = 0.2 \) W.  

(7)
Thus when no user approaches, the power of the low standby power socket is 0.2 W. The improved percentage is

\[
\text{Power without charger - Average power with charger} = \frac{0.521 \text{ W} - 0.2 \text{ W}}{0.521 \text{ W}} = 61.6\% 
\]

The power consumption of our socket has, therefore, been reduced to 0.2 W, an improvement of 61.6% when a user approaches. \( V_C \) and power consumption in respect to charging and discharging time are shown in Fig. 9.

![Figure 9](image)

Fig. 9. The power consumption in respect to charging and discharging time when a user approaches.

The Power cycle is 0.28 W. The power of the low standby power socket is 0.28 W when a user approaches. The improved percentage is \( \frac{0.564 \text{ W} - 0.28 \text{ W}}{0.564 \text{ W}} = 50.3\% \).

The power consumption of our socket has therefore been reduced to 0.28 W, an improvement of 50.3%. No matter whether the user is approaching or not, there is an improvement of the charger circuit of 61.6% or 50.3% respectively.

For the first charge the ultracapacitor is charged from 0 V to 5 V. When \( V_C < 3 \text{ V} \) the MCU cannot operate normally, and the control signal is not sent to the SSR2. Therefore the SSR2 should be turned on without any control signal. Fig. 10 shows the first charge for the ultracapacitor when our design is plugged into the AC power source.

![Figure 10](image)

Fig. 10. \( V_C \) and power consumption during first charging time.

In Fig. 10 the first charge time is 118 secs. The value has been derived from experimental measurements. Charging the ultracapacitor from 0 V to 5 V requires 118 secs and consumes more power during the first charge. The low standby power socket software module shown in Fig. 11 detects whether an appliance is working and eliminates the possibility of the SSR1 turning the power off as the user leaves. The charge circuit is designed to reduce the power consumption of the AC/DC converter in our design. Fig. 12 depicts the circuit design.

![Figure 11](image)

Fig. 11. Flowchart of the low standby power socket.

![Figure 12](image)

Fig. 12. Circuit of a socket with low standby power.
D. Implementation

We integrate both the power detector circuit, the charger and the ultracapacitor with the MCU in a board and connect other circuits to the board. We must bear in mind that the size of the PIR sensor must be small enough for it to be included inside the cases of most home appliances. Fig. 13 shows the implementation of a low standby power socket. Our design requires 3 V - 5 V DC from the AC/DC converter as the working voltage. For this prototype we have chosen an AC/DC converter with low power consumption.

III. MEASURING THE POWER CONSUMPTION OF THE LOW STANDBY POWER SOCKET

In our design the low standby power socket still requires power to work. Its average power consumption is 0.2 W when no user approaches. This is lower than the standby power of general home appliances. We measure the power consumption of the low standby power socket with a home appliance load in different situations: appliance only and with socket, both in standby state and work state. We use a microwave oven as an appliance load and show the results in Fig. 14.

<table>
<thead>
<tr>
<th>Appliance type</th>
<th>Appliance only, when no user is approaching</th>
<th>With socket, when no user is approaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave oven</td>
<td>2.8 W</td>
<td>0.2 W</td>
</tr>
<tr>
<td>TV</td>
<td>1.2 W</td>
<td>0.2 W</td>
</tr>
<tr>
<td>DVD player</td>
<td>1.5 W</td>
<td>0.2 W</td>
</tr>
<tr>
<td>Washing machine</td>
<td>1.4 W</td>
<td>0.2 W</td>
</tr>
</tbody>
</table>

IV. MATHEMATICAL VERIFICATION

Home appliances have two power states, standby state and work state. An appliance with a low standby power socket adds a third power state which we call “low standby state”. Fig. 15 shows the power state in the finite state machine. Fig. 16 shows the power consumption of state transition in a microwave oven with low standby power socket.
In the low standby state there is no user approaching and no appliance is in use. Thus as the SSR1 is turned off by the MCU, the appliance’s standby power is zero. The low standby state power consumption is 0.2 W, which comes from the low standby power socket. This amount is much less than the standby power of an appliance. An appliance with a low standby power socket increases its power consumption when it is in standby state or in work state. Fig. 17 shows the power consumption of a DVD player with a low standby power socket in standby state and in work state.

![Power Consumption Diagram](image)

**Fig. 17. Power consumption of a DVD player with low standby power socket in standby state and work state.**

The power consumption of an appliance in standby state and work state with our design can be measured by a power meter. In Fig. 17 the power consumption of a DVD player with low standby power socket in the standby state is standby power + 0.28 W, and the power consumption in the work state is work power + 0.28 W. Thus the low standby power socket saves power in the standby state. If an appliance in the low standby state is in daily use over a long period, the socket saves power; otherwise the socket consumes more power. Below we discuss the total power saving of our design with an appliance load.

First we define the probabilities of an appliance in the work state and in the standby state, without a low standby power socket.

\[
P_{\text{standby}} = \frac{\text{Time}_{\text{standby}}}{\text{Time}_{\text{work}} + \text{Time}_{\text{standby}}} \\
P_{\text{work}} = \frac{\text{Time}_{\text{work}}}{\text{Time}_{\text{work}} + \text{Time}_{\text{standby}}} \\
P_{\text{standby}} + P_{\text{work}} = 1
\]  

Then we define the probabilities of an appliance in the work state and in the standby state, with a low standby power socket, followed by the probability of an appliance in the low standby state.

\[
P_{\text{standby}} = \frac{\text{Time}_{\text{standby}}}{\text{Time}_{\text{work}} + \text{Time}_{\text{standby}} + \text{Time}_{\text{socket low standby}}} \\
P_{\text{work}} = \frac{\text{Time}_{\text{work}}}{\text{Time}_{\text{work}} + \text{Time}_{\text{standby}} + \text{Time}_{\text{socket low standby}}} \\
P_{\text{socket low standby}} + P_{\text{socket work}} + P_{\text{socket standby}} = 1
\]  

We denote the power consumption of each state as measured by a power meter as follows.

\[
\text{Power}_{\text{standby}} = \text{Power}_{\text{work}} + \text{Power}_{\text{socket low standby}}
\]

For an appliance with or without the low standby power socket the work state time is the same.

\[
\text{Time}_{\text{work}} = \text{Time}_{\text{work}} \text{ and } \text{Time}_{\text{standby}} = \text{Time}_{\text{socket low standby}}
\]

Thus \( P_{\text{work}} = P_{\text{socket work}} \) and \( P_{\text{standby}} = P_{\text{socket standby}} + P_{\text{low standby}} \)

\[
\begin{align*}
\text{Power}_{\text{socket work}} &= \text{Power}_{\text{work}} + 0.28 \text{ W} \\
\text{Power}_{\text{socket standby}} &= \text{Power}_{\text{standby}} + 0.28 \text{ W} \quad (11) \\
\text{Power}_{\text{socket low standby}} &= 0.2 \text{ W}
\end{align*}
\]

For power saving, the power consumption of an appliance without the low standby socket is greater than one with the low standby socket.

\[
\Rightarrow P_{\text{work}} \times \text{Power}_{\text{work}} + P_{\text{standby}} \times \text{Power}_{\text{standby}} > \\
P_{\text{work}} \times \text{Power}_{\text{work}} + P_{\text{socket}} \times \text{Power}_{\text{socket work}} + P_{\text{standby}} \times \text{Power}_{\text{socket standby}}
\]  

\[
\Rightarrow P_{\text{standby}} \times \text{Power}_{\text{standby}} >
\]

\[
\text{P}_{\text{work}} \times 0.28 \text{ W} + P_{\text{socket}} \times (\text{Power}_{\text{standby}} + 0.28 \text{ W}) + P_{\text{socket low standby}} \times 0.2 \text{ W} \quad (13)
\]

\[
\Rightarrow P_{\text{standby}} \times \text{Power}_{\text{standby}} + P_{\text{socket low standby}} \times \text{Power}_{\text{standby}} >
\]

\[
P_{\text{work}} \times 0.28 \text{ W} + P_{\text{socket}} \times (\text{Power}_{\text{standby}} + 0.28 \text{ W}) + P_{\text{socket low standby}} \times 0.2 \text{ W} \quad (14)
\]

\[
\Rightarrow P_{\text{socket low standby}} \times \text{Power}_{\text{standby}} >
\]

\[
P_{\text{work}} \times 0.28 \text{ W} + P_{\text{socket}} \times 0.28 \text{ W} + P_{\text{socket low standby}} \times 0.2 \text{ W} \quad (15)
\]

\[
\Rightarrow P_{\text{socket low standby}} \times \text{Power}_{\text{standby}} >
\]

\[
(P_{\text{work}} + P_{\text{socket}} + P_{\text{socket low standby}}) \times 0.28 \text{ W} = P_{\text{socket low standby}} \times 0.08 \text{ W} \quad (16)
\]

\[
\Rightarrow P_{\text{socket low standby}} \times \text{Power}_{\text{standby}} > 0.28 \text{ W} - P_{\text{socket low standby}} \times 0.08 \text{ W} \quad (17)
\]

\[
\Rightarrow P_{\text{socket low standby}} \times (\text{Power}_{\text{standby}} + 0.08 \text{ W}) > 0.28 \text{ W} \quad (18)
\]
Equation (18) presents the power saving limit of the low standby power socket. $P_{\text{low standby}}$ represents the probability of an appliance with the low standby power socket. The value must be larger than $(0.28 / (P_{\text{standby}} + 0.08))$ for power saving. For example, the standby power of a microwave oven is 2.8 W. To save power, a microwave oven with a low standby power socket must have a probability of no user approaching which must be more than 12.8%. For most families, with 8 hours at work or school and 8 hours of sleep, the probability of no user approaching is higher than 67%. Thus the low standby power socket is useful in most situations. Table III shows a comparison between our design and similar products.

<table>
<thead>
<tr>
<th>Product</th>
<th>Capability</th>
<th>Operation</th>
<th>Power consumption of device</th>
<th>Convenience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>Recharger</td>
<td>Auto</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Product B</td>
<td>PC peripherals</td>
<td>Auto</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Product C</td>
<td>Electric home appliances with standby power</td>
<td>Manual</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Our design</td>
<td>Electric home appliances with standby power</td>
<td>Auto</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

V. CONCLUSION

Although the standby power of electric home appliances is not great, it affects the electricity bill in the long run. In this paper we propose a design which reduces the standby power substantially. Our design, the low standby socket, which consumes only 0.2 W, is easy to set up and is inexpensive. In the long term our design saves very much power. Furthermore, our design, which is equipped not only with power detector circuits and with an MCU to control both an SSR and a PIR, is easily modified by programming and can then be applied to a new generation of appliances to save more power.

REFERENCES


Cheng-Hung Tsai is currently working toward the Ph.D. degree in Electronic Engineering at National Taiwan University of Science and Technology, Taiwan. He received his M.S. degree in electronic engineering from Fu Jen Catholic University in 2006. His research interests include low power system design and embedded computer systems.

Ying-Wen Bai is a professor in the Department of Electronic Engineering at Fu-Jen Catholic University. His research focuses on mobile computing and microcomputer system design. He obtained his M.S. and Ph.D. degrees in electrical engineering from Columbia University, New York, in 1991 and 1993, respectively. Between 1993 and 1995, he worked at the Institute for Information Industry, Taiwan.

Hao-Yuan Wang is currently working toward the M.S. degree in Electronic Engineering at Fu-Jen Catholic University, Taiwan. He received his B.S. degree in electronic engineering from Lunghwa University of Science and Technology in 2004. His major research is focus on consumer electronics products and microcomputer system integration design.

Ming-Bo Lin (S’90–M’93) received the B.Sc. degree in electronic engineering from the National Taiwan Institute of Technology (now is National Taiwan University of Science and Technology), Taipei, the M.Sc. degree in electrical engineering from the National Taiwan University, Taipei, and the Ph.D. degree in electrical engineering from the University of Maryland, College Park. Since February 2001, he has been a professor with the Department of Electronic Engineering at the National Taiwan University of Science and Technology, Taipei, Taiwan. His research interests include VLSI systems design, mixed-signal integrated circuit designs, parallel architectures algorithms, and embedded computer systems.