Design of Low-Power USB Audio System Based on LPM Protocol

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Abstract. Universal Serial Bus (USB) audio Devices was applied extensively in current mobile communication equipment, at the same time the low power consumption and high USB bandwidth must be satisfied, we design audio equipment based on USB2.0 High Speed (HS), adopt the latest USB Link Power Management (LPM) protocol issued by USB organization, use Field Programmable Gate Array (FPGA) as the main controller, USB2.0 HS physical layer interface (PHY) was designed externally, and then the USB audio class 3.0 equipment was realized to play music. System analysis and test results show that the system can transmit based on USB2.0 HS, and the average power consumption is lower than the USB1.1 audio equipment, has solved the demand of the high bandwidth and low power consumption of USB audio device effectively.

Keywords: USB LMP · Audio class 3.0 · USB2.0 HS · Intelligent energy saving · Low-powers

1 Introduction

USB audio devices [1] are removable external devices using USB channels and protocols for audio playback and recording. USB audio devices include many types, such as USB speakers, USB microphones, USB microphone arrays, etc. With the development of communication and networks technology [2–6], mobile communication devices are becoming increasingly slim and light. Therefore, the traditional 3.5 mm audio interface is gradually replaced by the USB interface [7], for that USB interface can be flattened, especially the USB type-c interface. There are growing types of peripherals based on USB interface, like USB audio device, one of the major categories. At the same time, the lightweight of mobile communication equipment strictly requires the endurance capability and peripheral power consumption [8]. This paper

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mainly studies one USB audio device design of low power consumption and high bandwidth based on USB LPM (USB2.0 Link Power Management).

2 Background

USB devices to be identified on host have some same features [9], including: device enumeration, reporting configuration descriptors, reporting class descriptors, and establishing data channels for efficient data interaction. For USB host, when enumerating USB device, class descriptor is used to determine device type, and configuration descriptor is used to select suitable driver for the device. After driver installed, the data channel of USB device is established successfully. Then, application layer software can access the USB drive by calling the device driver.

Taking the identification and operation project of USB headset (with microphone) device as an example. After USB audio device connected to USB host, by enumerating, host identifies it is audio device with function of playing and recording, belongs to USB headset. Then, according to configuration descriptor, host installs driver for the USB device [10] to establish two data transmission channels of iso out (synchronous output) and iso in (synchronous input). When host playing audio, data stream will flow from iso out to USB audio device. After decoding and ADC converting, sound can be heard through the device. The working principle is as follows (Figs. 1 and 2).

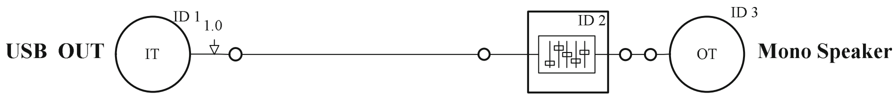


Fig. 1. Playing audio

When host recording audio, data stream will flow from iso in channel to host. After encoding and saving by host, the recorded file can be obtained. The working principle is as follows.

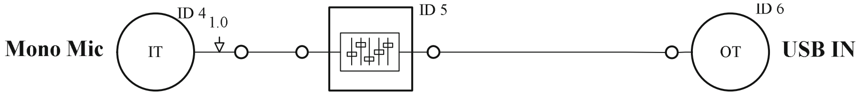


Fig. 2. Recording audio

Table 1. Design portfolio type of USB audio devices

USB connection bandwidth	USB version	USB audio class version
USB1.1 (USB2.0 full-speed) 12 mbps	USB1.1	Adc1.0
USB2.0 high-speed 480 mbps	USB2.0	Adc2.0
USB2.0 high-speed 480 mbps	USB2.1	Adc3.0

3 Design

Design portfolio of USB audio devices is shown below (Table 1).

Due to limitation of bandwidth and protocol version, USB1.1 cannot be applied to multi-channel and hi-fi. USB2.0 HS and ADC2.0 only satisfy bandwidth but not low power because of high consumption.

USB audio class has evolved into three versions, including ADC1.0 (audio device class 1.0), ADC2.0 and ADC3.0. Characteristics of ADC1.0 and ADC2.0 [11] are as follows.

☐ ADC 1.0:

(1) Adopt USB2.0 full-speed, bus transmission speed is 12 mbps;
(2) Support USB headphone devices
(3) Support USB microphone devices
(4) Support USB headset devices
(5) Support mute control and volume control
(6) Support audio streaming of pcm format

Basic USB audio devices can be implemented by ADC1.0. But with the development of audio devices and the requirement from multi-channel to multi-code and hi-fi, ADC1.0 can no longer support that. The performance of USB audio devices has been greatly improved until the advent of ADC2.0 based on USB2.0 HS.

☐ ADC2.0:

(1) Adopt USB2.0 high-speed, bus transmission speed is 480 mbps;
(2) Support mapping from physical channel to logical channel
(3) Support joint descriptor of audio interface
(4) Support sampling rate selection
(5) Support data stream of multiple encoding formats

Utilizing 480 mbps high bandwidth of USB2.0 HS and ADC2.0 standard, complex USB audio devices could be simulated, which meets the audio requirements of multi-channel, multi-code and hi-fi. To some extent, the ADC1.0 standard is replaced. However, with the popularity of mobile communication devices and the requirement of low power consumption, disadvantages of audio devices implemented by combination of USB2.0 HS and ADC2.0 are becoming increasingly prominent. It is characterized by high power consumption of USB2.0 HS devices [12], more than four times that of USB1.1 under the same conditions, which is exactly what this design needs to solve.

4 Design and Implementation

After USB protocol developed to V2.1, LPM (link power management) protocol was added [13]. Its basic concept is to let USB device entering suspend state to reduce power consumption when USB device has no data transmission requirements. The suspend status of USB devices could be long or short, which is called L2 in USB specification. Table 2 shows some status of USB LPM devices.

Table 2. Devices status of USB LPM

LPM states	Description
L0 (on)	Port is enabled for propagation of transaction signaling traffic
L1 (sleep)	Similar to L2 but supports finer granularity in use
L2 (suspend)	Port is disabled, Enter the low-power mode
L3 (off)	Port is not capable of performing any data signaling

State transition of USB devices is shown in the following figure (Fig. 3).

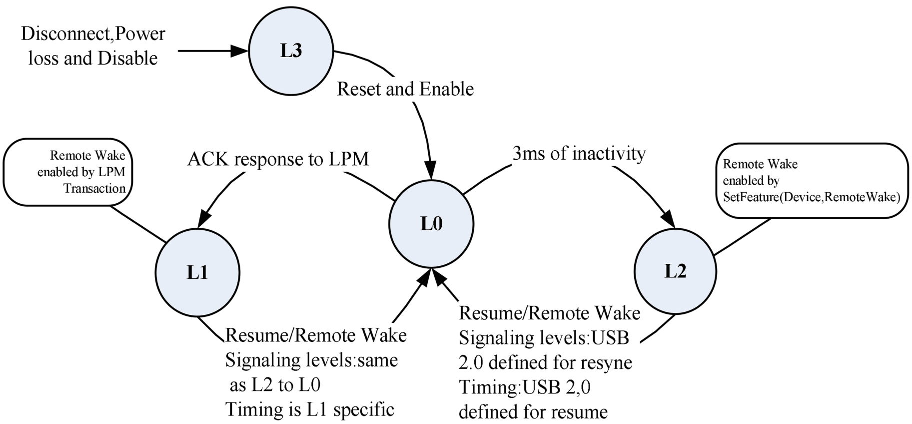


Fig. 3. USB state transition

Compared with normal USB standard, USB LMP standard has the advantage of L1 (Sleep) mode. Normal USB standard only supports L0, L2, and L3 but cannot let USB devices into low power mode in real time and wake up quickly.

After USB device enters L1 (Sleep), its own state, power consumption and wakeup mode are similar to L2 (Suspend) flow of normal USB. The difference is that speed of both entering and waking up from L1 (Sleep) is faster. The following table describes the characteristics of devices in and out of L1 (Sleep)/L2 (Suspend) (Table 3).

Table 3. Characteristics of USB devices in and out of L1/L2

Features	L1 (Sleep)	L2 (Suspend)
Entry	Explicitly entered via LPM extended transaction	Implicitly entered via 3 ms of link inactivity
Exit	Device or host-initiated via resume signaling; Remote-wake can be(optionally) enabled/disabled via the LPM transaction	Device or host-initiated via resume signaling; Device-initiated resumes can be (optionally) enabled/disabled by software
Signaling	Low and Full-speed idle	Low and Full-speed idle
Latencies	Entry: ~10 μs Exit: ~70 μs to 1 ms(host-specific)	Entry: ~3 ms Exit >30 ms(OS-dependent)
Link power consumption	~0.6 mW(data line-pull-ups)	~0.6 mW(data line-pull-ups)

The table shows L1 (Sleep) is a fast mode of L2 (Suspend).

Because of 480 mbps high bandwidth of USB2.0 HS, bus idle rate is very high during audio data streams transmission. When bus is idle, with USB LPM technology, device can enter L1 (Sleep) low power state to reduce the power consumption of entire USB audio device. However, ADC1.0 and ADC2.0 don't support USB LPM.

In order to meet requirements of USB audio device in low-power applications, recently USB organization has proposed the USB ADC3.0 standard [3]. With respect to ADC2.0, the biggest difference is USB LPM technology supporting, which offers possibility of low-consumption design of audio devices based on USB2.0HS. Design of this paper is on the basis of ADC3.0.

☐ Hardware implementation

System structure of low-power USB audio device in this paper is as follows (Fig. 4).

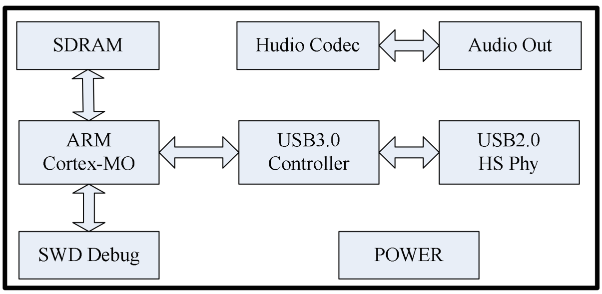


Fig. 4. Design of design of hardware structure

The system takes Altera Stratix III FPGA platform, low power CPU of arm-cortex-m0 with 30 MHz running frequency. Besides, it applies jtag/swd debug interface and

USB3.0 protocol analyzer to debug LPM protocol as well as using oscilloscope and high-precision multimeter to measure system function consumption (Fig. 5).

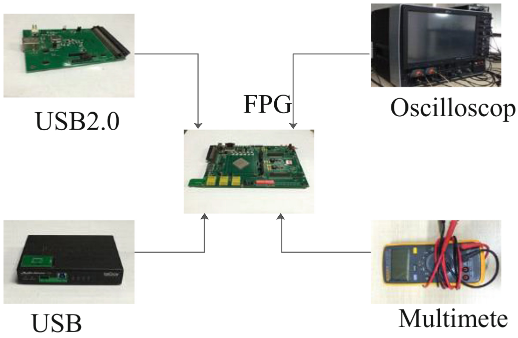


Fig. 5. Testbed and instrument

☐ Software Implementation

Under working mode, USB host allocates the data size delivered each time according to the bandwidth requirement of current audio data stream [14]. In order to maintain synchronization with audio data rate, host sends audio data stream periodically and makes devices into L1 (sleep) state to reduce power consumption at idle time. The software implementation process is as follows (Fig. 6).

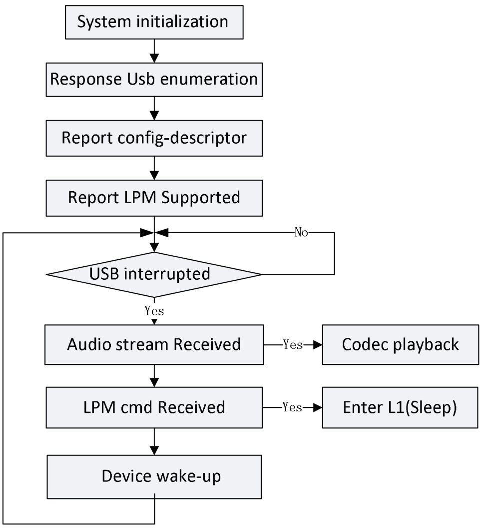


Fig. 6. Software implementation process

The software mainly implements two processes.

(1) Enter USB receiving audio data interrupt periodically, send audio data to decoder buffer pool to ensure the continuity of audio playback.
(2) Enter USB LPM instruction request interrupt periodically, configure system clock register and USB2.0 controller, and let the system enter L1 (sleep) state to reduce system power consumption.

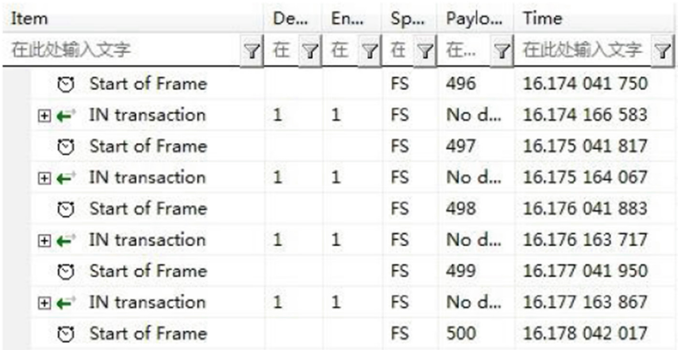
5 Test Results and Analysis

USB 3.0 protocol analyzer [10] works as concatenation between USB audio device and host to analysis protocol. The device supports USB2.0 Link Power Management protocol package. Test result is shown below (Fig. 7).

Fig. 7. Test screenshot of analytical instrument for USB protocol

Host successfully identifies the audio device supporting USB LPM technology.

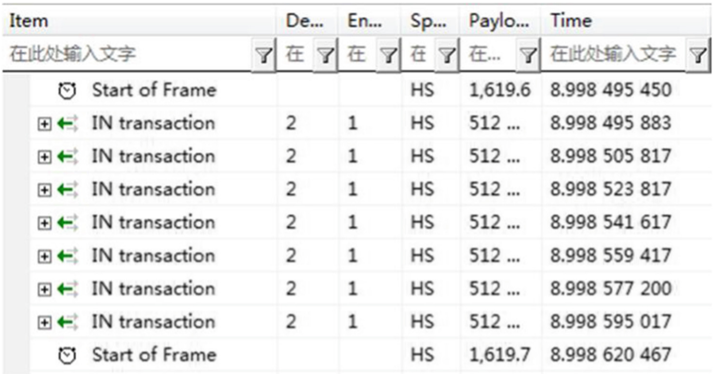
Data transmission of USB communication is identified by sof (Start of frame), and USB1.1 sends one sof per ms, as shown below (Fig. 8).



Item	De...	En...	Sp...	Paylo...	Time
在此处输入文字	在	在	在	在...	在此处输入文字
Start of Frame			FS	496	16.174 041 750
IN transaction	1	1	FS	No d...	16.174 166 583
Start of Frame			FS	497	16.175 041 817
IN transaction	1	1	FS	No d...	16.175 164 067
Start of Frame			FS	498	16.176 041 883
IN transaction	1	1	FS	No d...	16.176 163 717
Start of Frame			FS	499	16.177 041 950
IN transaction	1	1	FS	No d...	16.177 163 867
Start of Frame			FS	500	16.178 042 017

Fig. 8. Sending package interval of USB1.1

USB2.0 HS sends a micro sof per 125 μs, and 8 micro sofs form one sof, as shown below (Fig. 9).



Item	De...	En...	Sp...	Paylo...	Time
在此处输入文字	在	在	在	在...	在此处输入文字
Start of Frame			HS	1,619.6	8.998 495 450
IN transaction	2	1	HS	512 ...	8.998 495 883
IN transaction	2	1	HS	512 ...	8.998 505 817
IN transaction	2	1	HS	512 ...	8.998 523 817
IN transaction	2	1	HS	512 ...	8.998 541 617
IN transaction	2	1	HS	512 ...	8.998 559 417
IN transaction	2	1	HS	512 ...	8.998 577 200
IN transaction	2	1	HS	512 ...	8.998 595 017
Start of Frame			HS	1,619.7	8.998 620 467

Fig. 9. Sending package interval of USB2.0 HS

In setting of USB2.0 HS audio driver, 521-byte data is transmitted per micro sof (microframe). With 320 kbps bitrate, there are 40k byte data per minute which needs 80 micro sofs for transmitting. Therefore, for USB2.0 HS, the time for each micro sof is 125 us. When playing music of 320 kbps rate on host, actual power consumption is calculated by measuring following parameters.

Io: Phy current during audio data transmission
Is: Phy current in L1 (sleep) state
Tp: Periodic time of audio data transmission
Ts: Periodic time in L1 (sleep)

Following table shows the average value of Io, Is, To, Ts of multimetering (Table 4).

Table 4. Result of actual current and packet cycle test

Measurement	1	2	3	4	Mean
Io(ma)	29.43	29.76	30.27	29.16	29.65
Is(ma)	1.84	1.92	1.87	1.96	1.89
Tp(ms)	10	10	10	10	10
Ts(ms)	990	990	990	990	990

$$Ia = \frac{7 * 71n\,1 * 71}{7n\,1} \text{current formula} \tag{1}$$

The following table of actual power consumption of ADC1.0/ADC2.0/ADC3.0 is got by referring actual power consumption of normal USB1.1 audio equipment and getting la = 2.16 ma with the current calculation formula (Table 5).

Table 5. Actual power consumption of ADC1.0/ADC2.0/ADC3.0

USB audio class	Phy (system) average current (ma)	Audio bit rate
Adc3.0	2.16 ma	320 kbps
Adc2.0	29.65 ma	320 kbps
Adc1.0	7.54 ma	320 kbps

The above test data shows the average power consumption of this design is 71% lower than that of USB1.1 audio device, which solves power consumption problem of USB audio device on mobile communication device.

6 Conclusion

This paper mainly analyzes USB audio class 3.0 device based on USB2.0 Link Power Management additional protocol. The device meets data flow requirement by 480 mbps high-speed bandwidth of USB2.0 HS as all as realizing lower average power consumption than USB1.1 audio devices with the advantage of USB LPM. Experimental tests and calculations show that this study meets the need of low-power peripherals in modern mobile communication devices, and the high-speed bandwidth of USB2.0 HS provides solid foundation for the development of USB audio devices.

ABC3.0 technology is the latest standard proposed by USB organization for low-power devices. Currently, audio devices supporting adc3.0 have not been officially released on the market. This design validates the possibility of low-power USB audio devices and provides a basic implementation method. But, USB host is another key for the applying of low-power devices based on USB LPM technology. Host driver must effectively allocate USB bus bandwidth to achieve the real-time and efficient USB LPM scheduling mechanism, which is the next research of author.

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