A Systematic Analysis of The UART Transceiver Theory and Application

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Abstract. This article introduces the theoretical foundation and application of Universal Asynchronous Receiver/Transmitter (UART) in four chapters, including the history and structure of UART transceivers, and so on. UART is a kind of communication hardware using serial Asynchronous communication, which has the advantages of simple structure and good stability. It can convert serial data and parallel data to each other and transmit data between devices. It is widely used on various devices. In the 50 years since its invention, it has undergone many improvements and improvements. In the end, UART transceivers became one of the extremely important hardware in modern electronic technology. At present, UART transceivers are applied in many fields, including healthcare, the Internet of Things, and avionics. Its application in the fields of healthcare and the Internet of Things is of great significance, providing more possibilities for a more convenient life for humanity. Meanwhile, researchers are also attempting to continue improving the transmission speed of UART transceivers and reducing their power consumption.

Keywords: UART, Asynchronous Communication, Internet of Things.

1. Introduction

UART is the abbreviation for "Universal Asynchronous Receiver/Transmitter", which is a kind of communication hardware. It uses a serial means of communication. It can transmit data based on bits during the process of transmission, and follow the rule “the data which is input first will be output first". The received data will be transmitted according to the rules from low level to high level to achieve communication. It can achieve the conversion between parallel data and serial data [1]. UART transceivers are widely used in modern electronic technology. It is usually used to complete the data transfer between the devices. Due to its simple structure, low cost, and good communication stability, it has been highly favored since its invention. Up to now, the performance of UART has been improved gradually, but it still faces certain challenges and has a certain space for development.

This article divides the full text into two parts. In the first part, the theoretical rationale is described in detail. The second part mainly focuses on the specific application of the UART transceiver. In the theoretical basis section, the principle of the UART transceiver is first briefly described in this paper. Then, through some important time nodes, the history of the UART transceiver from its invention to the present day is reviewed. Later, this paper details the structure of UART transceiver, including the FIFO buffer, the baud rate generator, the sending module, the receiving module and their functions. Finally, this paper explains the asynchronous serial communication mode adopted by UART transceiver, and analyzes its structure of character frames. When discussing the application of UART, this article mainly focuses on three aspects. They are the applications of UART in the fields of healthcare, the Internet of Things, and avionics. During the analysis, this article summarizes the main functions of UART transceivers in various applications with pictures, and lists examples of UART applications in corresponding fields.

This article provides a detailed summary of UART transceivers and sorts out various aspects of UART transceivers. This provides a quick way for subsequent researchers to understand UART transceivers and lays a solid foundation for researchers to continue developing and improving UART transceivers.

2. Theoretical basis

2.1. Brief Introduction of the Principle

The UART transceiver works based on the UART serial port communication protocol. Based on this agreement, people define the format of one-frame data for serial port communication as a standard. A single frame of data needs to include start bits, data bits, parity bits, stop bits, and idle bits. At the same time, the port rate is also one of the most important parameters in the serial port communication. It can determine the rate at which the data is transmitted between the two communication parties. The two parts involved in the communication should have the same parameters in order to communicate normally, which is stipulated by the UART communication protocol.

UART can work in multiple modes, including simplex, half-duplex, and full-duplex. In single work communication, only a single direction of transmission can be performed. In half-duplex, whether the transmitter or the receiver, only one of them is communicating at each time. If the transmitter transfers data, the receiver is idle, and this is true as well for the receiver. In full-duplex mode, the transmitter and receiver can work simultaneously.

2.2. Development History

As early as that year, in 1971, to achieve communication between computers and external devices, Bell invented the UART communication protocol. It can solve the problem of converting parallel data into serial data. In the early stages of UART development, it was often used to transfer data between the host machine and the external devices. Subsequently, in 1978, Brown proposed using UART integrated circuits to encode information, which opened a new chapter in the application of UART [2].

In the 1980s, the research on UART transceiver was developing rapidly [3]. Its potential for use in microprocessors was tapped, and relevant textbooks was compiled perfectly. These results lay the foundation for later researchers to make more important progress in the field of UART transceiver.

By the end of the 1990s, Harris Corporation invented the chip named 82C52.Chen Wei used it to achieve high speed communication between two PCs [4]. It had a baud rate of 1 MHz, the upper limit of the UART transceiver transmission rate was greatly increased. This result provided valuable ideas for young researchers to continue to solve the problem of slow transmission rate of UART transceiver.

Time has arrived in the 21st century, research on UART transceivers still focuses more on improving transmission rates and reducing power consumption. In 2013, Dipanjan Bhadra and his team successfully designed a low-power UART transceiver using asynchronous techniques [5]. His design reduced the UART power consumption to a quarter of that of the synchronous designs. In 2020, A. K. Gupta and his team successfully designed, simulated, integrated, and implemented a high-speed universal asynchronous receiver and transmitter (UART) using the Verilog Hardware Description Language (HDL language) [6]. And then they validated it. Their achievements in scientific research brought the baud rate of UART up to 4Mbps.

2.3. The structure of UART transceiver

The UART transceiver mainly consists of four modules as shown in Figure 1.

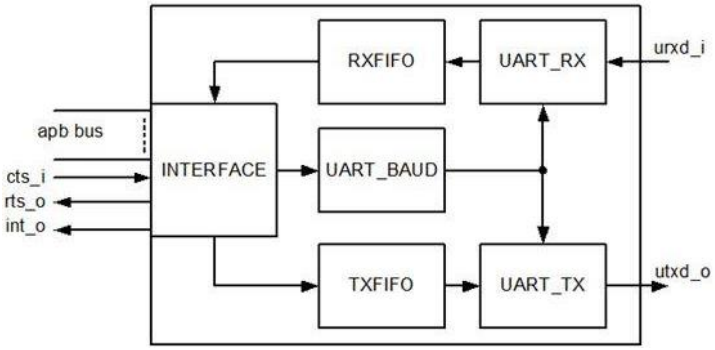


Figure 1. Structure of the UART transceiver

They are the FIFO module, the Baud rate generator, the sending module, and the receiving module. The four modules each have corresponding functions to ensure that the UART transceiver can operate normally. UART has the characteristics of relatively simple structure, and for another UART device, there are usually only three wires: the transmitting end (TX), the receiving end (RX), and the grounding end. The transmitting end is responsible for outputting serial data. The function of the receiving end is to receive serial data. In addition, there are other interfaces for transmitting parallel data with other devices, as shown in Figure 2.

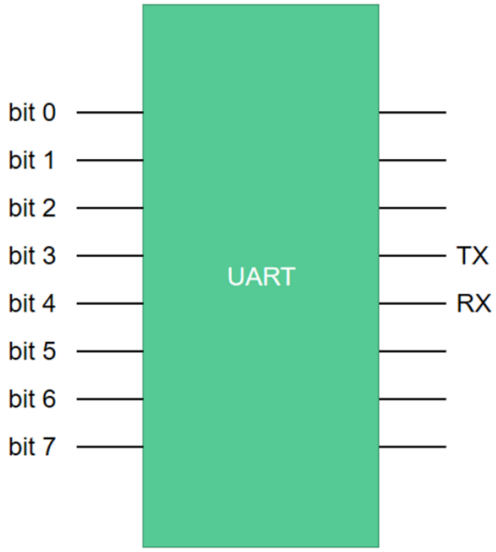


Figure 2. Interfaces of the UART

2.4. FIFO buffer

FIFO is the abbreviation for First Input First Output. It is a type of buffers, mainly used as a buffer to temporarily store data when generation and usage of data are not synchronized. It follows the rule that the data written first will be read first [7]. With the continuous development of modern electronic technology, the CPU (Central Processing Unit) processing speed is getting faster and faster. However, the UART transceiver does not have a fast transmission rate. This can cause the CPU to be used when data is sent or retrieved to UART. And then this will affect the processing speed of the CPU and even the whole system. Currently, FIFO is needed to cache the high-speed and continuous data flow to reduce the burden of CPU and improve the utilization efficiency of CPU. In addition to reducing the burden of CPU, FIFO also has the role of preventing data loss and improving the transmission speed of data [8]. So, the FIFO is very necessary to exist in the UART transceiver.

2.5. Baud Rate Generator

In data transmission, baud rate is an important parameter that describes its speed, usually expressed in bps. The baud rate generator is a very important component for the UART transceiver. Because the UART does not have a clock, it must use the baud rate for timing synchronization. In this way, it ensures that the data can be transmitted correctly. In this process, the receiver will start timing after receiving the start bit signal until the stop bit of the data is received. In actual communication, it is difficult to fully synchronize the port rate clocks of the receiver and transmitter terminals. Therefore, it is also important to consider the impact of baud rate error on UART.

2.6. Sending Module

The main function of the sending module is to send the data. It contains TXFIFO, data sending logic unit, inspection logic unit and other modules. It derives the corresponding transmission frequency division coefficient from the baud rate. When TXFIFO is not empty, it reads the data to be sent from the buffer and sends out a frame of data under the control of the counter. It usually remains at a high

level when there is no data transfer. Secondly, the sending module will send the content according to the format specification of the data, and convert the parallel data into serial data sending [9].

2.7. Receiving Module

The receiving module is constructed similar to the sending module, and also has units such as counters. When it receives the data, it transforms the serial data into parallel data and packages it. In this process, it processes the received data according to the baud rate as standard. The receiving module is also a necessary module in the UART transceiver, which, together with the sending module, serves as a bridge connecting two UARTs.

2.8. Serial Communication

The UART transceiver adopts a serial communication mode. It is a communication method that transmits data in the order of bits. In this way, UART uses high and low levels to represent the 1 and 0 of the ASCII code. When data is transmitted, one byte of data is sent one bit at a time, and the data bytes are reconstructed after the eight bits received by the receiver [10].

Serial communication, which only sends or receives one bit of data at a time, has the characteristic of stable transmission and is widely used in various controllers. Moreover, the device structure of serial communication is generally simpler than that of devices using other methods. If full duplex communication is used, the connection between two devices only requires two serial data cables, as shown in Figure 3.

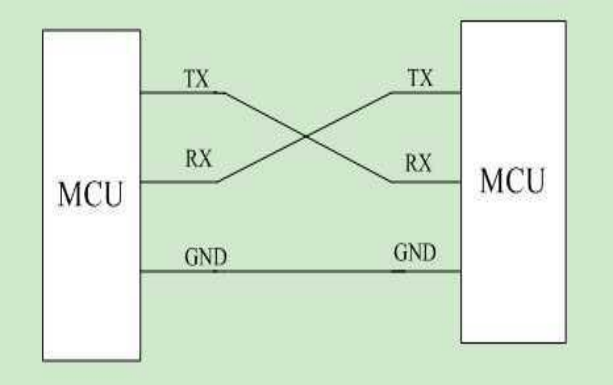


Figure 3. Connection of the serial communication equipment

Such a concise construction is also one of the reasons why it is widely used.

2.9. Asynchronous Communication

Asynchronous communication is a communication mode by transmitting a frame composed of characters. In this mode, each character frame can be separated at any time, but each bit in the character frame is transmitted at a fixed time. Each character frame needs to be marked with a start and stop bit to indicate the start and end times.

2.10. Structure of Character Frame

In UART transceivers, both sending and receiving data need to be done in the form of character frames. Each character frame is specified as a fixed format. A frame of data generally includes start bits, data bits, parity bits, stop bits, and the rest are idle bits, as shown in Figure 4 [11].

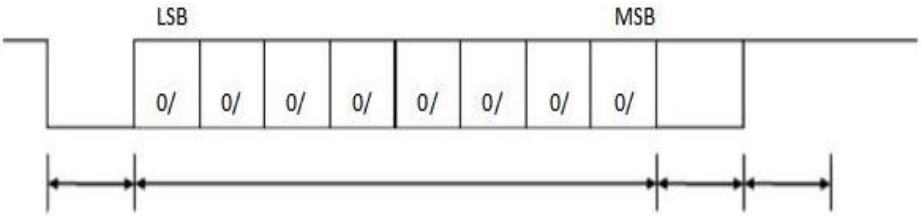


Figure 4. Format of Character Frame

The idle bit is specified as a high level. The start bit is the symbol for the start of data transmission and is specified as a low-level signal. The purpose of this regulation is to form a clear distinction from idle bits. The data bits can have five to eight bits to accommodate the required information. Odd and even parity bits can be selected to determine whether there has been an error in the data during transmission. The parity bit is not necessary in a frame of data, and the designer of UART can remove them as needed. The stop bit is at the end, indicating the end of a frame of data. When UART detects a stop bit, it will stop receiving data.

When the format of data is incorrect, the UART transceiver may issue a warning of data error or fail to function.

3. Application Scenarios of UART

3.1. Application in the Medical Field

In the medical field, UART transceivers are mainly used to transmit data between detection devices and computers. It first obtains detection data from the detection device, and then transmits it to the computer for analysis, as shown in Figure 5.

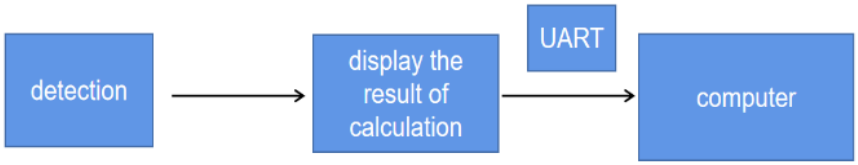


Figure 5. Workflow

It establishes a bridge between computers and detection equipment.

In 2019, V. Ryabchevsky and his team applied UART to the human-machine interface of the electromyography recorder [12]. The EMG recorder can accept electrical signals from human muscles and convert them to electromyogram or electrocardiogram output. They applied the UART at the interface of the chip. The port D lines were configured for hardware operation with the UART (Universal Asynchronous Receiver-Transmitter) interface, which connects to a PC and exchanges data and downloads software through the internal boot record of the microcontroller. The remaining lines controlled the switches (PD2-PD7). This study calculated the optimal operation of the UART register, solved the problem of interrupted UART interface and improved the accuracy of myography.

In 2020, A. D. Elbaeva's team developed an instrument and a computer analyzer algorithm for non-invasive diagnosis of atherosclerosis [13]. When the instrument was working, first the blood cholesterol level would be measured. Then the calculation results would be displayed. And finally the test results would be transmitted to the computer through the UART interface and the USB/UART converter. This study turned the idea of noninvasive diagnosis of cholesterol levels into reality and made an effective contribution in the medical field.

3.2. Application in the Internet of Things

In the Internet of Things, UART transceivers are often used to connect microprocessors and various other devices, such as GPS, Bluetooth, etc., as shown in Figure 6.

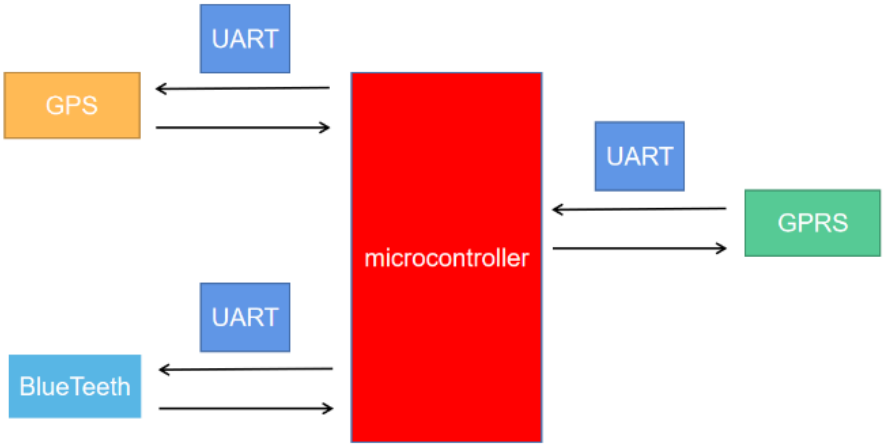


Figure 6. The UART is applied to the Internet of Things

Using UART, a microprocessor can exchange data with multiple devices, greatly improving the efficiency of the Internet of Things.

In 2018, R. R. Pahlevi's team proposed enhancements to UART and SPI to improve node performance on the Internet of Things platform [14]. They connected UART with FPGA board, which solved the expandability and speed of the Internet of Things platform. It only took 1.08737 seconds for the 10,000-bit data to be transmitted and received on the UART by the GA, which was 67.3% faster than ATmega328, and can scale up to four UART scalability issues.

In 2019, L. V. Bogdanov proposed an improved Wi-Fi device with a UART bridge [15]. In this study, radio signals were first emitted from the device and then received by the Wi-Fi to UART bridge. The signal is converted by the bridge and then transmitted to the microcontroller by the UART transceiver. Finally, the microcontroller would control the hardware based on data to complete the entire interaction process of the Internet of Things, as shown in Figure 7.

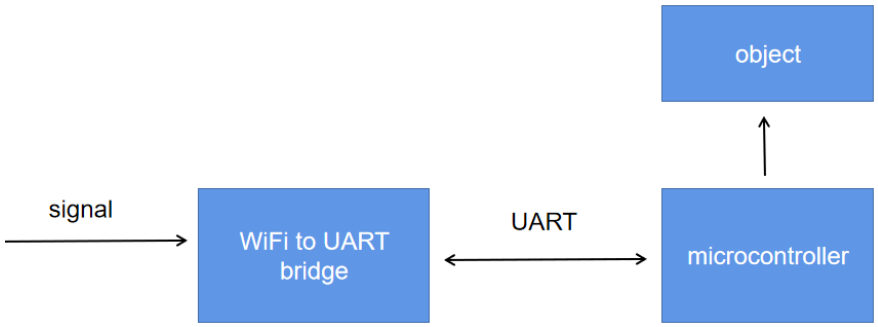


Figure 7. Wi-Fi to UART bridge

During this process, the microcontroller required a UART boot loader to be able to transmit data normally. This study mainly focused on the field of adapter development and had practical significance. It could be used to update the firmware of microcontrollers based on Wi-Fi, in line with the trend of the development of the Internet of Things.

In 2022, B. Jeevan's team combines UART with Internet of Things applications [16]. They set up UART transceivers on microcontrollers and external devices to communicate in single, half-duplex, and full-duplex mode. This enabled the microcontroller to transfer data with each data for controlling peripherals and reading device information.

3.3. Application in Aviation Electronics

In 2018, Weihui Liu and others applied UART technology to the attitude acquisition of quad-rotatory aircraft [17]. They established a connection between the MPU6050 module and the upper computer using the UART transceiver. First, the MPU6050 module collected various attitude information of the aircraft, such as pitch angle, rotator speed, etc. And then these posture-related data would be transmitted to the UART transceiver. Finally, it would be transmitted to the upper computer

by the UART transceiver. This attitude acquisition method improved the speed of reading and writing serial interface data and reduced the complexity of the whole system. It provided a universally applicable method for aircraft attitude acquisition.

A. S. Keerthi Nayani team provided a design for applying UART transceivers to missiles in 2019 [18]. In this design, UART was used for duplex communication between each remote data acquisition unit (RDAU) and the master data acquisition unit (MDAU). At first, each RDAU collected various data such as stress and pressure from each subsystem, and then transmitted the data to the corresponding UART. The final data would be sent by UART to the MDAU. As shown in Figure 8.

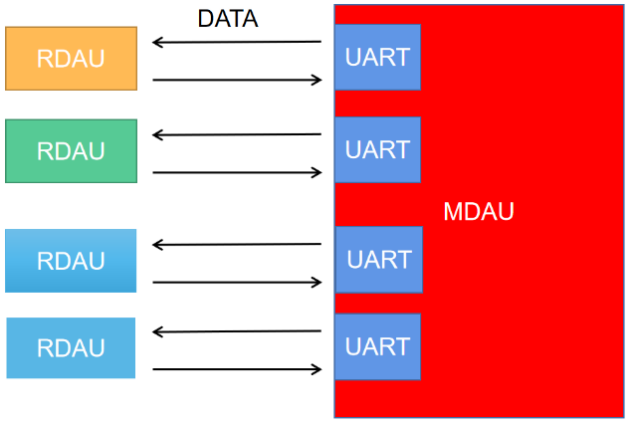


Figure 8. The UART applied to the missile sub-module communication

In this design, the application of UART improved the accuracy and reduced the impact of noise on the transmission data, simplifying the data transmission among the sub-modules of the missile.

In 2021, Shibo Xing 's team developed a UART-based multi-bus avionics equipment detection system [19]. In this study, UART was applied to airborne data bus-based communication between subsystems. It could transmit the device's own information, status information and maintenance information to each aero-electronic device. And it had a very close relationship with the aero-electronic device detection system.

4. Conclusion

This paper focuses on the theoretical basis and application of UART, and elaborates various aspects related to UART transceiver. In the 50 years since the invention of UART, the technology of UART transceiver has been continuously developing and widely used in all aspects. In many aspects of modern life, such as medical care, the Internet of Things, UART transceivers are very important. In addition, UART transceiver makes the existing technology better applied.

However, UART transceivers also face some challenges. Increasing data transmission speed and reducing power consumption have always been a problem for researchers in UART fields. In the future, based on the UART application section in this paper, the author believes that the future direction of UART transceiver will probably focus on the Internet of Things and medical fields. The UART speed will be further improved and the power consumption will be reduced.

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