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A Comparative Review of Peripheral Interfaces and Communication Protocols in Embedded Systems

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Abstract. Peripheral interfaces are widely used in modern electronic systems, serving as essential bridges that allow controllers to exchange information with the external environment. Without these interfaces, microcontrollers and processors would not be able to communicate effectively with sensors, actuators, or other digital devices. Over the years, a variety of interfaces and communication protocols have been developed, each designed with specific advantages in terms of speed, reliability, cost, and application scenarios. By conducting a literature review, this paper provides a comparative analysis of several commonly used interfaces, as well as higher-level protocols employed in embedded systems and industrial applications. The review highlights their fundamental characteristics, operational principles, and typical use cases, while also examining the trade-offs between performance and complexity. The findings suggest that an informed selection of peripheral interfaces is crucial for system efficiency, scalability, and long-term reliability.

Keywords: Peripheral Interfaces, Communication Protocols, Embedded Systems, System Efficiency

1. Introduction

The peripheral interface could be separated into a physical part and a protocol part. The nature of the physical interface determines the shape and interaction of this interface. Parts of the interface protocol, such as the transmission frequency, determine how far this interface can transmit, the interference, and the immunity to interference. Other parts of the interface protocol can express other properties, such as scalability. Resistance-based measuring devices are widely used to measure important physical parameters such as electric current, pressure, temperature, light intensity, and so on [1]. These measuring devices all need to be connected via some kind of interface to the controller for processing.

New interfaces are likely to come from modifications of older interfaces, such as Improved Inter-Integrated Circuit (I3C), wireless serial ports, Inter-IC for Wearables (I2We) [2], which transmits the Inter-Integrated Circuit (I2C) through conductive fabrics, and so on. These interfaces introduce new transmission methods or additional cables, etc., to the original interface. Compatibility with the original protocol is largely maintained.

In the form of transmission, interfaces can be categorized into wired and wireless interfaces. Wireless transmission is widely used because it can realize non-contact transmission, does not affect

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the movement of equipment, and is characterized by low cost over long distances. Wireless transmission usually transmits information by modulating wireless electromagnetic waves. This results in large conflicts and interference in the same frequency signal. Some protocols circumvent the problem by performing frequency hopping communication in a certain frequency range, such as Bluetooth and Wi-Fi. Wired transmission is characterized by higher immunity to interference, better stability, and higher transmission rates.

The directions and aspects for which different interfaces are suitable can be obtained after studying the transmission methods and protocols through a literature review. This information can be used to recommend and guide the development of new products.

2. Peripheral interface

A peripheral interface is a way that connects a computer's CPU, memory, and peripheral devices, or between two peripheral devices, or between two machines via a bus.

Peripheral interfaces can be categorized as simplex, half-duplex, and full-duplex in terms of transmission modes. Simplex only supports a single device to send information to another device. A receiver may not send information to a transmitter. Both devices, on half-duplex and full-duplex, can send information to each other. Half-duplex allows only one direction of information to be transmitted at a time, while full-duplex allows information to be sent and received at the same time.

Peripheral interfaces can be differentiated into serial and parallel interfaces in terms of how the data is sent. In serial interfaces, data is transmitted bit by bit. Parallel Serial interfaces can be shielded from interference by differential transmission, referencing twisted pair cables, and so on. Parallel interfaces after shielding, serial interfaces can generally achieve higher transmission frequencies and longer transmission distances than parallel interfaces. The data in the parallel interface is sent to the receiver at once according to the number of data lines. The lengths of the transmission lines need to be equal to ensure that no data loss or data misalignment occurs during transmission. In a serial interface, the lengths of the lines do not need to be strictly equal between different groups.

In terms of synchronization, peripheral interfaces are divided into synchronous and asynchronous transfers. Synchronous transmission in which the transmitter and receiver rely on a common signal line to maintain synchronization. No prior negotiation of data rate is required in synchronous communication. Stable timing is provided through clock signal lines, which are suitable for high speeds and large data transfers, as the clock signal ensures that the data is received correctly. Asynchronous interfaces do not require clock signals and rely on start and stop bits to define the beginning and end of a data frame for sending and receiving data. Asynchronous interfaces generally require a pre-negotiated communication rate to allow both parties to parse the information. Asynchronous interfaces simplify the interface design by eliminating the need for additional clock lines, making them suitable for low-speed and short packet transfers, but the start and stop bits take up bandwidth that is underutilized.

Peripheral interfaces are categorized into hot-swappable and non-hot-swappable interfaces based on their physical characteristics. Hot-swappable interface devices can be inserted into a new device or unplugged during system operation without affecting system stability. Hot-pluggable interfaces usually have a special design, such as the signal line being shorter than the power line, to ensure that the power supply is connected first, so that both references are at the same voltage. Most of the hot-plug devices support plug-and-play, that is, there are common drivers and protocols that enable the insertion of the device, and the device can automatically detect its form, without the need to reconfigure or manually install the driver.

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3. Wired interface

3.1. Video interface

Commonly used video-dedicated wired interfaces include High Definition Multimedia Interface (HDMI), DisplayPort (DP), Digital Visual Interface (DVI), Video Graphics Array (VGA), RGB, Composite video, S-Video, MCU (Intel 8080 or Motorola 6800), and so on. Most of these interfaces are digital, while VGA, Composite video, and S-video are analog. Analog signals are less resistant to interference. Table 1 shows the details of different types of signals and their characteristics.

Table 1. Signal types of video interfaces [3,4]

Signal type	Digital Signal					Analog Signal		
Interface	HDMI	DP	DVI	RGB	MCU	VGA	Composite video	S-Video
Serial or parallel	Serial	Serial	Serial	parallel	Parallel	Analog parallel	N/A	N/A
Data rate	48.0Gbit/s	80Gbit/s	9.9Gbit/s	3 times of clock rate	9/4 times of clock rate	N/A	15Mbps	25Mbps
Standard Clock rate	12,000MHz	20,000MHz	1,650 MHz	No standard	No standard	N/A	3.58MHz/4.43MHz	3.58MHz/4.43MHz
Channel	4 differential pair	4 differential pair	6 differential pair	24 signal channel for RGB888	18 signal channel	3	2 (Y/C)	1
Efficiency	8b/10b (80%) 16b/18b (88.9%)	8b/10b (80%) 128b/132 (97%)	8b/10b (80%)	24c/27c (88.9%)	24c/27c (88.9%)	No coding	No coding	No coding
synchronization	synchronous	synchronous	synchronous	synchronous	asynchronous	asynchronous	carrier modulation	carrier modulation
duplex	simplex	simplex	simplex	simplex	half-duplex	simplex	simplex	simplex

For HDMI, DP, and DVI, these three interfaces are not essentially different, and only the transmission rate and authorization methods are different. The RGB MCU interface is mostly used in embedded systems. This interface does not have a standard clock frequency, which depends on the frequency that the signal line can withstand, as well as the frequency that the chip can withstand. VGA, Composite video, and S-Video are more susceptible to interference as analog signals. HDMI, DP, and DVI include checksum information to detect incorrect data and retransmit or correct it through the protocol's checksum, whereas RGB and MCU interfaces lack error-correcting capabilities and are not suitable for long-distance data transmission.

3.2. Data transfer and device interface

Commonly used data transfer and device interfaces are Universal Serial Bus (USB) serial, Peripheral Component Interconnect Express (PCIe), and serial ports (Table 2).

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Table 2. Types of USB serial

Signal type	USB Serial				
Interface	USB 1.x	USB2.x	USB3.2 gen1	USB3.2 gen2	USB3.2 gen2x2
Serial or parallel	Serial	Serial	Serial	Serial	Serial
Data rate	12Mbit/s	480Mbit/s	5Gbit/s	10Gbit/s	20Gbit/s
Clock rate	12Mhz	480Mhz	5Ghz	10Ghz	10Ghz
Channel	1 differential pair	1 differential pair	2 differential pair	2 differential pair	4 differential pair
Efficency	No coding	8b/10b (80%)	8b/10b (80%)	128b/132b(97%)	128b/132b(97%)
synchronization	Synchronous/Asynchronous				
duplex	Half-duplex	Half-duplex	duplex	duplex	duplex

The USB series protocol uses high-frequency differential pairs to achieve high-speed signal transmission. A transmission rate of 480 Mbps is achieved on a pair of twisted differential lines. This makes it ideal for wired transmission over long distances. Its universal protocol covers most human-machine interaction devices and is driver-free and hot-pluggable. Table 3 shows the types of PCIe Series.

Table 3. Types of PCIe series

Signal type	PCIe Series				
Interface	PCIe 1.0	PCIe 2.0	PCIe 3.0	PCIe 4.0	PCIe 5.0
Serial or parallel	Serial	Serial	Serial	Serial	Serial
Data rate	2.5Gbit/s	5Gbit/s	8Gbit/s	16Gbit/s	32Gbit/s
Clock rate	2.5Ghz	5Ghz	8Ghz	16Ghz	32Ghz
Channel	1 differential pair	1 differential pair	1 differential pair	1 differential pair	1 differential pair
Efficency	No coding	8b/10b (80%)	128b/130b (98.5%)	128b/130b (98.5%)	128b/130b (98.5%)
synchronization	Synchronous(default)/Asynchronous				
duplex	duplex	duplex	duplex	duplex	duplex

Table 4. Types of serial ports [5-10]

Signal type	Serial ports							
Interface	I2C	SPI	CAN	SDIO	UART	RS232	RS485	RS422
Serial or parallel	Serial	Serial	Serial	Serial	Serial	Serial	Serial	Serial
Data rate	100 Kbit/s (Standard), 400 Kbit/s (Fast), 1 Mbit/s (Fast Plus), 3.4 Mbit/s (High Speed)	data rate = clock rate	125Kbit/s 1Mbit/s	100Mbit/s 200Mbit/s For 4 lanes	Depends on clock	Up to 115 kbit/s	up to 10 Mbit/s	up to 10 Mbit/s

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Table 4. (continued)

Clock rate	100Khz 400Khz 1Mhz 3.4Mhz	Up to 150Mhz for some MCUs	125Khz 1Mhz	50Mhz / 25Mhz(Default/High Speed)	Up to 12.5Mhz or 24Mhz depends on chips	N/A	N/A	N/A
Channel	1 clock line 1 data line	2 data channel 1 clock channel 1 select channel	1 differential pair	1/4 single line	1 Tx 1 Rx	1 Tx 1 Rx	2 differential pair (Tx/Rx)	1 differential pair
Efficency	~80%	No coding	47.6%–72.7%	>90%	8b/10b (80%)	8b/10b (80%)	8b/10b (80%)	8b/10b (80%)
synchronization			Synchronous				Asynchronous	
duplex	Half-duplex	duplex	Half-duplex	Half-duplex	duplex	duplex	Half-duplex	duplex

Experiments comparing I2C, UART, and SPI have already been conducted [11]. This article provides comparisons with more wired serial protocols (Table 4).

Serial interfaces encompass a wide range of protocols, each with its own specific purpose. A standard serial data packet typically includes one start bit, eight data bits, and one stop bit. Some serial data packets also include a parity bit to verify the integrity of the data packet. This protocol is well-suited for simple communication between two devices, such as data transmission in an agricultural precision seeding parameter monitoring system [12]. However, serial communication requires predefined data packet formats and transmission baud rates, which prevents the implementation of driver-free and universal protocols.

4. Wireless interface

4.1. Short wireless distance protocol

Commonly used short-range wireless communication protocols are IEEE 802.11 (Wi-Fi) (Table 5) and Bluetooth (Table 6).

Table 5. Information of Wi-Fi protocols

Wi-Fi	bands	Nick Name	Data rate
802.11a	2.4Ghz	Wi-Fi2	54Mbit/s
802.11b	5Ghz	Wi-Fi1	11Mbit/s
802.11g	2.4Ghz	Wi-Fi3	54Mbit/s
802.11n	2.4/5Ghz	Wi-Fi4	600Mbit/s
802.11ac	2.4/5Ghz	Wi-Fi5	6000Mbit/s
802.11ax	2.4/6/5Ghz	Wi-Fi6	9600Mbit/s

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Table 6. Information of Bluetooth protocols

Bluetooth	bands	distance	Data rate	power
2.1	2400MHz~2483.5MHz	10	2.1Mbit/s	high
4.0	2400MHz~2483.5MHz	50	1Mbit/s	BT-medium BLE-low
4.2	2400MHz~2483.5MHz	50	1Mbit/s	BT-medium BLE-low
5.0	2400MHz~2483.5MHz	300(long distance mode)	1Mbit/s	BT-medium BLE-low
5.2	2400MHz~2483.5MHz	300(long distance mode)	1Mbit/s	BT-medium BLE-low

USB 3.0 data transmission uses 2.0-5.0 GHz differential signals. There are some articles that reflect that the USB 3.0 serial port data transmission will have an effect on WLAN data transmission [13,14]. The radiation generated by this frequency can easily interfere with wireless communications in this frequency range, especially cables that are not grounded and shielded. Wi-Fi and Bluetooth are greatly affected in this range, and only Wi-Fi in the 6 GHz frequency range can escape this interference. The solution using common mode filters can reduce noise by 10-30 dB [15].

In terms of transmission speed and stability, Wi-Fi has a significantly higher transmission speed than Bluetooth. However, Wi-Fi also consumes more power than Bluetooth, especially Bluetooth Low Energy. Overall, wireless networks are more suitable for high-power scenarios that require both networking and connection to the external Internet. Bluetooth is more suitable for low-power scenarios that only require networking.

4.2. Low-power mesh network protocol

In IoT communication technology, ZigBee, LoRa, and NB-IoT are three common protocols. ZigBee has a transmission range approximately twice that of standard Bluetooth mode, but its transmission rate is limited to 250 Kbit/s. Its automatic network repair feature makes it well-suited for IoT cluster deployment. LoRa can achieve transmission ranges of several kilometers or more in open terrain, but its rate is limited to around 50 Kbit/s. NB-IoT is based on 4G cellular networks, making this communication protocol more suitable for smart city development. For urban applications, it can leverage existing infrastructure for unlimited-distance communication, which makes it easy to make for a network of city devices such as smart cities, connected streetlights, and traffic monitoring, though it is costly and requires coordination with telecom operators.

4.3. Special protocol

RFID protocols are highly secure, with a communication range generally within 10 meters. However, there is no active communication protocol, and communication must be initiated by the reader. RFID cards using CPU cards offer better transmission encryption than magnetic stripe cards and are not susceptible to theft due to information leakage.

Near Link SLB operates in the 5.8 GHz frequency band, which avoids interference from protocols such as USB 3.0. In this frequency band, its coverage and diffraction capabilities are also better than those of 6 GHz Wi-Fi 6. SLE's low-power transmission distance and speed are also better than those of Bluetooth.

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Infrared transmission is an early wireless transmission protocol, but different infrared devices follow very different protocols and require the controller to be aligned with the device, and do not have the ability to penetrate walls.

5. Conclusion

This study conducted a comparative analysis of common communication protocols, including both wired and wireless transmission technologies, focusing on key parameters such as transmission range, data rate, network stability, and deployment feasibility. Through this comparison, this paper gained a clearer understanding of the trade-offs involved in protocol design, which provides a foundation for selecting appropriate communication technologies in different Internet of Things (IoT) scenarios.

The significance of this research lies in its ability to inform protocol selection decisions for future networked systems. As wired and wireless protocols jointly support the infrastructure of the modern Internet, understanding their advantages and limitations is crucial for developing more efficient, scalable, and adaptable systems. Moreover, evaluating these technologies contributes to reducing potential incompatibilities and redundancies between protocols, which is especially important in large-scale deployments such as smart cities or industrial IoT environments.

However, this study is primarily based on theoretical comparisons and literature analysis. No experimental data were collected to validate transmission performance, particularly with regard to distance limitations and resistance to interference. Future research should include empirical testing under real-world conditions to enhance the reliability of findings. In addition, emerging technologies such as 5G, Wi-Fi 7, and mesh networks warrant deeper investigation to better understand their role in next-generation communication systems.

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