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A Survey on IoT Modules: Architecture, Key Technologies and Future Directions

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Abstract. The Internet of things (IoT) is a promising technology which offers the seamless connectivity of the global world via heterogeneous smart terminals. As the core component of IoT intelligent terminals, IoT modules integrate various electronic devices such as baseband chips, radio frequency modules and positioning modules, etc., and form single devices which can be embedded into different types of IoT terminals. In this paper, we present a survey on IoT modules. The architecture and the components of the IoT modules are briefly introduced. Then, the classification of IoT modules is discussed, which mainly includes cellular communication modules and non-cellular communication modules. One of the most widely used cellular communication modules, i.e., narrow-band IoT (NB-IoT) module, is further introduced and the characteristics of the module are examined in detail. In addition, the design and manufacturing process of IoT modules is summarized and the key technologies are discussed. Finally, the future research and development directions of IoT modules are specified.

Keywords: Internet of Things · IoT modules · NB-IoT architecture

1 Introduction

In recent years, the Internet of things (IoT) has received considerable attention and IoT technologies and applications have experienced rapid development. It is expected that the number of connected IoT devices will reach 41.6 billion by 2025 [1]. In order to reduce production cost, simplify software development procedure and reduce product release cycle time, terminal manufactures seek to exploit module-based technique and develop various IoT related devices based on IoT modules [2–5].

In IoT modules, various electronic components including baseband chips, radio frequency (RF) modules and positioning modules, etc., are integrated into unified devices which can then be embedded into different types of IoT terminals. By using IoT modules, the design and manufacturing process of IoT terminals can be simplified [6]. As one of the key components of IoT devices, the performance and characteristics of IoT modules play an important role in determining the cost and performance of the terminals.

In this paper, a survey on IoT modules is presented. We first introduce the architecture and components of IoT modules, then, discuss the classification of IoT modules

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and elaborate the characteristics of narrow-band IoT (NB-IoT) modules. The design process and key technologies of IoT modules are further summarized. Finally, the future research and development directions of IoT modules are specified.

2 Functional Architecture of IoT Modules

This section discusses the general functional architecture of IoT modules. As shown in Fig. 1, the functional architecture of an IoT module mainly consists of baseband chip, RF module, global navigation satellite system (GNSS) module, memory chip, power management module and peripheral interface, etc. The detail descriptions of the components contained in the module architecture will be discussed as below.

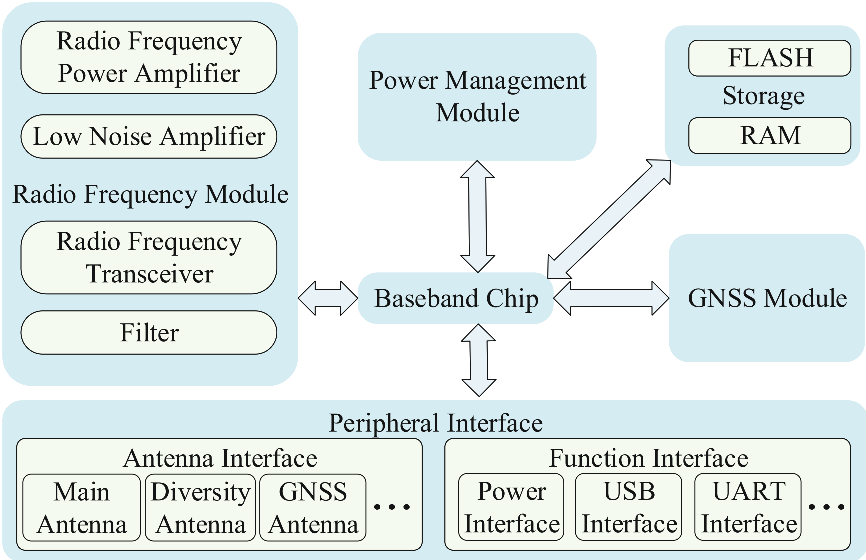


Fig. 1. General architecture of IoT modules.

The baseband chip in IoT modules is mainly responsible for processing baseband signals and protocols. The specific functions may include baseband codec, timing control, digital system control, RF control, power saving control and man-machine interface control, etc. According to the underline chip design technology, baseband chips can be divided into analog baseband chips and digital baseband chips, where analog baseband chips mainly process analog signals, such as audio signals, whereas digital baseband chips deal with digital signals, such as ARM core, digital input/output (I/O), etc.

2.1 RF Module

As the transmitters and receivers of IoT modules, RF modules are mainly responsible for sending and receiving the RF signals of IoT terminals. In order to process RF signals properly, certain signal processing operations including frequency synthesis, power amplification and signal filtering are commonly conducted. To implement the functions of RF signal processing, an RF module is composed of an RF transceiver, a power amplifier, a low noise amplifier and a filter, etc.

The receiving process of RF modules is briefly described as follows: An RF signal is received at the RF transceiver, and then processed by a low noise amplifier. The amplified signal is input into a mixer circuit to obtain the baseband in-phase/quadrature (I/Q) signal, which is sent into the baseband chip for further processing. The transmission process of RF modules is of the reverse order as that of receiving process. Specifically, the output of the baseband circuit, i.e., the I/Q signal is sent into the modulation circuit inside the transceiver, and then modulated to generate an RF signal. After being amplified and filtered by the power amplifier circuit, the RF signal is sent out from the antenna.

2.2 GNSS Module

GNSS module is the general positioning and navigation module which are capable of receiving positioning related information from various systems including global positioning system (GPS), BeiDou navigation satellite system (BDS), and Galileo positioning system, etc. GNSS module is composed of satellite constellations, receivers and signal detection circuits. The GNSS module in IoT terminals is widely used in the applications such as surveying and mapping, transportation, public safety, etc. In these application scenarios, the main functions of the GNSS module is to provide weather information, high-precision positioning, navigation and time information for the terminals [7].

2.3 Power Management Module, Storage, Peripheral Interface

The power management module in IoT terminals is mainly responsible for providing stable and reliable power supply for terminals. Its main functions include on/off control, voltage control, power supply and detection, and terminal charging control, etc. In addition, some specific power management operations can be applied so as to reduce the energy consumption of the IoT terminals during working and idle hours and prolong the service time of the terminals in battery power supply mode.

The storage unit in IoT terminals is mainly designed for storing data and information, including system and software parameters of wireless communication modules and the data generated by terminals. The storage units are divided into external flash memory and random access memory (RAM), where the flash memory is used to store system parameters, program codes and important data, and RAM is utilized to cache the temporary data when the terminals are operating.

According to various requirements and functions of IoT terminals, different peripheral interface units should be designed. The major peripheral interfaces include antenna interfaces and functional interfaces, where the antenna interfaces are in general composed of main antenna, diversity antenna, GNSS antenna, Bluetooth antenna and wireless fidelity (Wi-Fi) antenna, etc., and the functional interface provides the input and output of various signals for the IoT terminals, which can be power supply, universal serial bus (USB) flash disk, universal subscriber identity module (USIM), universal asynchronous receiver-transmitter (UART), security digital (SD) card, analog or digital audio, and general-purpose I/O (GPIO) interface, etc.

3 Classification of IoT Modules

According to the utilized wireless communication technologies, IoT modules can be categorized into two types, i.e., cellular modules and non-cellular modules, among which cellular modules are further divided into 2G modules, 3G modules, long-term evolution-category 1 (LTE-Cat1) modules, 5G modules, narrowband-IoT (NB-IoT) modules and enhanced machine-type communication (e-MTC) modules, and non-cellular communication modules can be divided into Wi-Fi modules, Bluetooth modules, ZigBee modules, long range (LoRa) and Sigfox modules.

With the global spread of 4G and the rapid development of 5G related technologies, as well as the gradual exit of 2G, 3G cellular applications, the migration of IoT services from 2G, 3G to 4G and 5G cellular systems has become an important trend. Consequently, an integrated system architecture consisting of NB-IoT, LTE-Cat1, 4G and 5G is expected to offer efficient and diverse support to IoT applications in a cooperative manner. Specifically, NB-IoT technology is mainly used for low-rate scenarios, and LTE-Cat1 is expected to become the long-term IoT standard which meets the requirement of medium-speed IoT applications. Benefited from the advanced performance, 5G technology will be employed to the IoT application scenarios which require high speed, low delay and high reliability.

It is apparent that various IoT modules and technologies are of highly different characteristics and offer diverse service performance. In Table 1, we summarize the characteristics, performance, cost and application scenarios of existing IoT modules. In practical applications, corresponding IoT modules can be chosen by jointly considering the related metrics.

4 NB-IoT Technology and Modules

Compared with LTE-Cat1 and 5G modules, NB-IoT modules have been widely used and received considerable attention in recent years [8,9]. This section presents an overview of NB-IoT technology and modules.

4.1 An Overview of NB-IoT Technology

NB-IoT technology was introduced in 3GPP Rel-13 as one of the cellular IoT (CIoT) technologies for low power wide area network (LPWAN) applications [10,11]. Evolved from LTE-Cat1, NB-IoT allows operators to offer service support to massive IoT

Table 1. Summary of IoT modules and technologies

Access technology		Band	Range	Peak Rate	Module cost	Application scenarios
Cellular	5G	450–6000 MHz, 24250–52600 MHz	–	2.1 Gbps	1000–3000 RMB	Cellular vehicle-to-everything, digital billboard, wise information technology of med
	LTE-Cat1	1.88–1.9 GHz, 2.32–2.37 GHz, 2.575–2.635 GHz	–	10 Mbps	100–150 RMB	Wearable device, intelligent security, smart agriculture, logistics tracking
	3G	1.88–1.9 GHz, 2.01–2.025 GHz	–	42 Mbps	100–150 RMB	POS, wearable device, smart home
	eMTC	1.88–1.9 GHz, 2.32–2.37 GHz, 2.575–2.635 GHz	–	1 Mbps	100–150 RMB	Wearable device, vehicle management, electronic billboard
	NB-IoT	1.88–1.9 GHz, 2.32–2.37 GHz, 2.575–2.635 GHz	–	$\leq$100Kbps	60–80 RMB	Smart meter reading, smart grid monitoring, smart parking
	GSM	890–915 MHz, 935–960 MHz, 1.71–1.784 GHz,1.805–1.879G MHz	–	100–300 Kbps	$\leq$20 RMB	SMS message, voice calls
Non-cellular	LoRa	868 MHz, 915 MHz	15 km	50 kbps	2 RMB	Smart street lamp, smart home
	Sigfox	915–928 MHz	20 km	100 bps	1 RMB	Mining industry, tunneling
	ZigBee	868 MHz, 915 MHz, 2.4 GHz	$\leq$1 km	250 Kbps	1 RMB	Smart street lamp, smart factory
	Wi-Fi	2.4 GHz, 5 GHz	100 m	54 Mps	5–50 RMB	Smart home, remote video transmission, home gateway
	Bluetooth	2.4 GHz	50 m	2 Mbps	5–50 RMB	Wise information technology of med, wearable device, smart home

devices by utilizing existing network technology and part of available spectrum. Since the spectrum bandwidth assigned for NB-IoT technology is relatively narrow, which is equal to 180KHz, the technology is named as narrow-band IoT technology. To implement NB-IoT technology in cellular networks, various modes can be applied, including in-band, guard band or independent carrier.

Compared with the short distance communication technologies such as Bluetooth and ZigBee, etc., NB-IoT technology offers wide coverage, massive connection and low power consumption, which will be discussed briefly as follows.

Wide Coverage. In practical applications, NB-IoT is usually deployed in the frequency region less than 1 GHz. Since the utilized spectrum in NB-IoT is relatively low, especially compared to other wireless transmission technologies, such as 5G, LTE and WiFi, better signal transmission performance can be obtained, resulting in wider coverage area. It has been demonstrated that NB-IoT technology is expected to achieve an extended coverage of 20dB compared to commercially available legacy GPRS devices.

Massive Connection. In general NB-IoT applications, users may not transmit or receive data packets frequently. Indeed, the 3GPP NB-IoT service model assumes that the average number that users access the network is 0.467 per hour, which is relatively low. In addition, the size of the transmitted packets in NB-IoT applications is relatively small, resulting in short access and transmission time. In order to reduce the signaling overhead of NB-IoT, some signaling procedures, e.g., control side and the user side optimization, are simplified compared to LTE technology. Therefore, the connection capacity of NB-IoT network is enhanced significantly. According to 3GPP TR45.820, NB-IoT is capable of supporting 50,000 connections per sector.

Low Power Consumption. In order to save the power consumption of NB-IoT modules and terminals, various power saving technologies are utilized. For instance, power saving mode (PSM) and extended discontinues reception (eDRX) are both applied to greatly extend the battery life of NB-IoT terminals.

4.2 NB-IoT Modules

Designed based on NB-IoT technology, NB-IoT modules offer some desirable features, as discussed in detail in this subsection.

Low Complexity. Compared to LTE modules, NB-IoT modules mainly support frequency division duplexing (FDD) half-duplex mode, i.e., the modules does not need to deal with sending and receiving simultaneously, hence, the complexity is reduced greatly. In contrast to LTE modules which mainly use multiple antennas, NB-IoT modules in general support single antenna, thus reducing the complexity required for RF processing. Moreover, the lower rate requirements and low bandwidth of NB-IoT applications lead to simplified chip processing. As a result, the complexity of NB-IoT modules is significantly lower than that of LTE modules.

Low Cost. NB-IoT modules are usually operate in low data rate, low power consumption and small bandwidth environment. For low data rate communications, no large caching space is required, hence, the size and cost of the modules decrease accordingly. Benefited from low power consumption and small bandwidth applications, the requirements on RF circuits and signal processing algorithms can be reduced, leading to low module cost. Furthermore, operating in half-duplex mode, applying single antenna and sharing spectrum with LTE technology also result in low cost required to design and produce NB-IoT modules.

Diverse Interfaces. To meet the product development needs of different users, NB-IoT modules provide a wealth of external interfaces, such as antenna interface, subscriber identification module (SIM) card interface, universal asynchronous receiver-transmitter (UART) interface, etc. NB-IoT modules can also support multiple network protocol stacks, such as transmission control protocol/Internet protocol (TCP/IP), user datagram protocol (UDP), constrained application protocol (CoAP), message queuing telemetry transport (MQTT), etc.

Multi-Band Operation. As the frequency bands utilized by different IoT terminals may be different, in order to meet the transmission requirements of multiple frequency bands, NB-IoT modules are capable of operating in multiple frequency bands, thus supporting the application demand of terminals in various frequency bands.

Broad Applications. NB-IoT has a wide range of application scenarios, including environment monitoring, smart home, smart power grid monitoring, smart agriculture, intelligent remote meter reading, etc., [9]. Figure 2 shows several application examples of NB-IoT modules.

Fig. 2. Application samples of NB-IoT modules.

5 Design and Manufacturing Process and Key Technologies of IoT Modules

To design and manufacture IoT modules, various procedures are required. This section introduces the process of designing and producing IoT modules, and then discusses several key technologies.

5.1 Design and Manufacturing Process of IoT Modules

The process of designing and producing IoT modules mainly involves chip selection, schematic diagram design, printed circuit board (PCB) drawing, module debugging and testing, etc. This section discusses the steps of the process briefly.

Chip Selection. Selecting suitable IoT chips is the first and important step in designing and producing IoT modules. The characteristics including transmission performance, power consumption and available interfaces should be jointly considered when selecting chips. Furthermore, the cost, stability and reliable supply of the chips are key factors for commercial use, and thus should also be taken into account.

Schematic Diagram Design. Based on the selected chips, the schematic diagram of the IoT module can be designed. During this process, the stability of module structure, electromagnetic compatibility and the difficulty of large-scale manufacture should be considered.

In order to ensure that the modules work coordinately and effectively in various electromagnetic environments, electromagnetic compatibility issue should be addressed. In particular, the modules should be able to suppress various types of external interferences effectively. The difficulty of large-scale manufacture should also be considered ed in designing schematic diagram. Apparently, the desired schematic diagrams are expected to lead to relatively high process yield and facilitate large-scale production.

PCB Drawing. Once the design of a schematic diagram is completed, we may start drawing the PCB accordingly. During PCB board drawing phase, the issues such as RF requirement, stability, structure, aesthetic degree of the PCB board should be considered collectively. The general process of drawing a PCB board mainly consists of the following steps, i.e., component parameters create, schematic diagram input, parameter setting, PCB layout, PCB wiring, design verification, and computer aided manufacturing (CAM) file output. In the above design process, PCB layout and wiring are important steps as the quality of PCB layout and wiring may affect the performance of the whole module and terminal significantly.

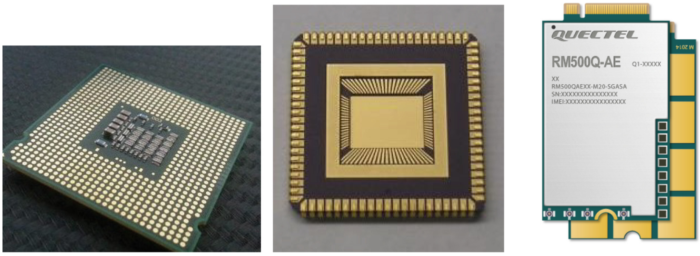
Module Debugging. To debug IoT modules, both hardware circuits and software need to be debugged. For hardware debugging, RF circuit debug is of particular importance. Since RF circuits are responsible for transmitting and receiving RF signals, the transmission parameters including transmit power and phase errors, etc., and the receive performance such as sensitivity and reception level should be debugged.In addition, certain circuit function debugging may also be conducted according to the requirements of IoT modules.Software debugging is also performed so as to ensure that the software embedded in IoT modules can operate properly.

Module Testing. In order to guarantee that the designed IoT modules can achieve the required functions and performance metrics, module testing is mandatory which involves a series of measurement, judgment, adjustment and re-measurement processes [12]. In general, module testing includes functional testing, performance test, stability test, aging test and certification test, etc.

5.2 Key Technologies

The key technologies of designing and manufacturing IoT modules consist of packaging technology, power consumption control technology and the consistency in hardware interface and software design, etc. This section discusses the key technologies in detail.

Module Packaging Technology. The module packaging technology is a particular circuit integration technology which is utilized to implement the secondary development of the chips and achieve high-density integration of the chips and circuits in the module. There are mainly three packaging modes commonly used for IoT modules, i.e., land grid array (LGA) packaging [13], leadless chip carriers (LCC) packaging [14] and M.2 packaging [15].



(a) LGA packaging (b) LCC packaging (c) M.2 packaging

Fig. 3. Samples of IoT module packaging.

Using LGA packaging technique, all the contacts are located on the PCB of IoT modules, and therefore the backside of the module looks like a grid. Figure 3(a) shows a sample of IoT module using LGA packaging.

The LCC packaging employs no-pin and patch packaging technique. An IoT module using LCC packaging technology is encapsulated by a patch, and all the pins are curved inwardly at the edge of the module so as to reduce module volume. Compared to LGA packaging technology, the debug and weld process of the modules using LCC packaging technique is relatively difficult. Figure 3(b) plots a sample of LCC packaging module.

The M.2 packaging modules are packaged in accordance with the M.2 interface specification. The M.2 interface, also known as the next generation form factor (NGFF), is a new interface scheme launched by Intel Corp., which specifies a variety of interface types and dimensional specifications. An IoT module using M.2 packaging technology offers the advantages of fast transmission speed, small module size, and strong compatibility, etc., and are widely used in IoT application scenarios [15]. Figure 3(c) plots an example of M.2 packaging module.

Power Consumption Control Technology. In order to achieve low power consumption, IoT modules adopt PSM and eDRX power-saving technologies which reduce the power consumption of modules through increasing sleep time [16]. For an IoT module in PSM state, its transceiver is turned off and the access layer related functions are disabled, therefore, the power consumption resulted from signal transmission, receiving and processing is reduced significantly. By applying eDRX technology, IoT modules stay longer time in sleep state instead of sensing paging channel. Since the power consumption of the modules in sleep state is much lower than that in other states, power saving can be achieved [17].

Interface Consistency. To design a general IoT module, which can be applied to diverse IoT application scenarios, the requirement of various applications, the size, packaging mode and pin layout of the module and the cost issue should be considered comprehensively. In particular, through subdividing the interfaces according to

IoT industries, and defining specific power supply interface, module control and status interface, etc., different types of IoT modules and terminals can be designed and manufactured, and the terminal cost and research and development (R&D) cycle can be reduced as well.

In order to ensure the ease of use of IoT modules and the smooth interaction between IoT modules and the cloud and business platforms, it is necessary to conduct comprehensive software planning and design, and stress the consistency and compatibility of software interfaces. In particular, the basic attention (AT) command set interface of IoT modules should be of satisfactory consistency and compatibility so as to meet the basic needs of the IoT applications. Furthermore, to enable the efficient connection between IoT modules and the cloud and business platforms, the suitable software operating system should be chosen and the communication software development kit (SDK) interface should be designed.

6 Future Development Directions of IoT Modules

This section summarizes several important future development directions of IoT modules.

6.1 Miniaturization, High Integration and Standardization

With the explosive growth of IoT connections, wearable application scenarios such as smart bracelets have become one of the important scenarios of IoT applications. Such scenarios require portable, lightweight and miniaturized IoT modules. To design and manufacture miniaturized IoT modules, highly integrated chips can be employed. In addition, advanced manufacturing process can be applied to further reduce the size of IoT modules, in particular, 7 nm or even 5 nm manufacturing process has been adopted recently in making miniaturized IoT modules.

Aiming to facilitate the design and manufacturing of IoT terminals and boost the development of IoT applications, the standardization of IoT modules has become an important development trend. The standardization of IoT modules involves various aspects, e.g., the standard size of IoT modules, standardized hardware interfaces, standardization in pin positions and functions, and the support of pin-to-pin backwards compatibility, etc. By leveraging standardized IoT modules, the difficulties in developing IoT terminals and replacing new modules can be alleviated, and the cost of IoT terminals can be reduced as well.

6.2 eSIM Technology-Based IoT Modules

At present, pluggable SIM cards are commonly used in mobile communication systems and IoT applications. However, the rapid development of IoT services puts forward higher requirements on smart cards. For instance, certain harsh application environments require the SIM cards to have specific physical and electrical characteristics, such as high environmental temperature and humidity, etc. In some IoT applications, frequent reading and writing operations may occur, which pose requirement to the service life and reliability of the SIM cards. To enable remote access of IoT modules, the SIM cards should support remote configuration, remote activation, and user identity change over the air.

To meet the rising requirements of IoT applications, embedded SIM (eSIM) card technology has emerged in recent years. The eSIM cards are implemented by integrating a physical chip, much smaller than the SIM cards, into IoT modules. The eSIM cards offer many advantages, e.g., high temperature resistance, shock resistance, and super anti-interference ability, which are more suitable for use in future IoT applications. In addition, by applying software control and intelligent technology, eSIM card can achieve remote control and management conveniently.

7 Conclusion

The IoT module is a carrier of the IoT terminal to access the network, which is an important part of the end-to-end solution. This paper first provided a brief introduction to the IoT module, and then analyzed the architecture of the IoT module and briefly analyzed the function of each part. Then the modules have been divided into cellular communication modules and non-cellular communication modules according to the different communication modes,and NB-IoT module has been specifically introduced. The approximate design process of the IoT module was described below, and three key technologies existing-packaging technology, power consumption control technology and consistency of hardware interface and software design were introduced. Finally, based on the above analysis, the future development direction of the networking module technology have been expressed.

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