Ambient Power-enabled IoT

Second Edition of
"Zero Power Communication"

CONTENT

FOREWORD

In recent years, the industry has adopted a number of IoT (Internet of Things) technologies to fulfil the communication requirements for various target usage scenarios. Nevertheless, as the boundaries of IoT usage expand, more scenarios emerge and features like ultra-low cost, very small form-factor, low power consumption and maintenance-free are becoming of increasing importance for field deployment and operation. The newly emerged Ambient Power-enabled IoT technology (a.k.a. Ambient IoT technology), which integrates environmental radio power harvesting, ultra-low power communication and low-power computing, is anticipated to meet all the stringent requirements and to become one important candidate of next generation technology for Internet of Things.

01

1.1 The status-quo of IoT

Wireless communication technology flourished since 1990s. Digital mobile communication system has evolved from 2G, 3G and 4G to 5G today, with each generation to serve the needs of voice calls, messaging service and mobile Internet during their time of service. Nevertheless, a trend is becoming more and more clear - requirement on IoT communication rises together with societal shifts and economic development with an accelerating pace.

Technologies and standards related to the mobile IoT have been developed and evolved since 2010. Among them, 3GPP (3rd Generation Partnership Project) has standardized series of IoT technologies such as MTC (Machine Type Communications), NB-IoT (Narrow Band IoT) and RedCap (Reduced Capability UE). Techniques used in MTC and NB IOT, such as reduced bandwidth, single antenna, reduced peak rate, half duplex and reduced transmission power have significantly lowered the cost of IoT terminals. Furthermore, power consumption of IoT terminals is greatly reduced by the introduction of eDRX (enhanced Discontinuous Reception) and PSM (Power Saving Mode). At the same time, existing IoT solutions like MTC/NB-IoT can also support a large number of terminals for simultaneous network accessing to meet the need of massive connection.

Apart from 3GPP, standardization organizations like IEEE also released technologies tailored for IoT. IEEE 802.11 standardized a series of WiFi technologies, for example 802.11b/n are widely used for local area network based IoT. GS1/ISO published RFID technology for short-distance stock take application in a point-2-point mode. LoRa protocols defined by LoRa Alliance is another type of wide area IoT technology known by large coverage, low power consumption, large capacity and low cost.

1.2 Unsatisfied communication requirements of IoT

Existing technologies such as MTC and NB-IoT have achieved low cost, low power consumption and massive connection of IoT terminals, thus they are able to meet the communication requirements of IoT in many scenarios. However, there are still many situations where communication requirements cannot be satisfied with existing technologies, such as:

Harsh communication environment

Certain scenarios of IoT may face extreme environmental conditions such as high temperature, extremely low temperature, high humidity, high pressure, high radiation or high-speed movement. Some examples of these hazardous circumstances include ultra-high voltage power stations, railways carrying high-speed trains, environmental monitoring in over/under temperature areas and industrial production lines. In these scenarios existing IoT terminals will not work due to factors like failure of conventional power supplies. In addition, maintenance of IoT devices (e.g., recharging or replacing batteries) becomes challenging under extreme conditions. Battery-free and maintenance-free IoT devices are highly desired for these application scenarios.

Scenarios where ultra-small devices are requested

For some IoT communication scenarios, e.g., goods traceability, commodity circulation and smart wearables, small form-factored devices are requested for practical use. For example, IoT devices used for commodity management in the circulation are normally in the form of small tags and is embedded into the commodity packaging. As another example, small and light-weight wearable devices can improve the user experience while meeting communication needs.

Scenarios asking for ultra-low cost IoT devices

Many IoT scenarios ask for ultra-low cost IoT devices to enhance competitiveness over other alternative technologies. For examples in logistics or warehousing scenarios, in order to facilitate the management of a large number of goods in circulation, devices can be attached to each package of pallet in order to complete the accurate management of the whole logistics process. These scenarios require that the cost of IoT devices be sufficiently competitive.

In sum, abovementioned scenarios request battery-free, ultra-low power consumption, very small size and ultra-low cost IoT devices. Meanwhile, typical applications demand IoT systems provide sufficiently large network coverage and system throughput as well as flexible network deployment ability. Additionally, various IoT communication requirements exist across private consumption scenarios such as enabling smart terminal devices to access IoT devices to support smart home and smart wearable applications.

Existing IoT technologies are either limited by their power consumption levels so that have to rely on wired or battery power, or cannot provide the requested communication range and networking abilities. Cost of IoT devices and system maintenance also needs to drop to reduce total cost of ownership (TCO). How to meet these unsatisfied communication requirements of IoT and to better serve the economic and social development is a problem worthy of discussion and study.

1.3 Position and vision of Ambient IoT

Ambient IoT technology utilizes key techniques such as RF energy harvesting, ultra-low power communication and low-power computing. An Ambient IoT device powers up itself by harvesting and accumulating small amount of energy contained in radio waves, light, heat and motion. In this way the device does not rely on conventional batteries. Furthermore, ultra-low power communication and low-power computing technologies make the device achieve an extremely simplified RF and baseband circuit structure, which can greatly reduce the cost, size and energy consumption. Therefore, Ambient IoT is expected to enable battery-free devices to meet the communication needs of IoT with ultra-low power consumption, very small size and ultra-low cost.

Due to the battery-free nature, such kind of devices are also named as Ambient IoT devices and the corresponding communication procedure may also be called Ambient IoT communication.

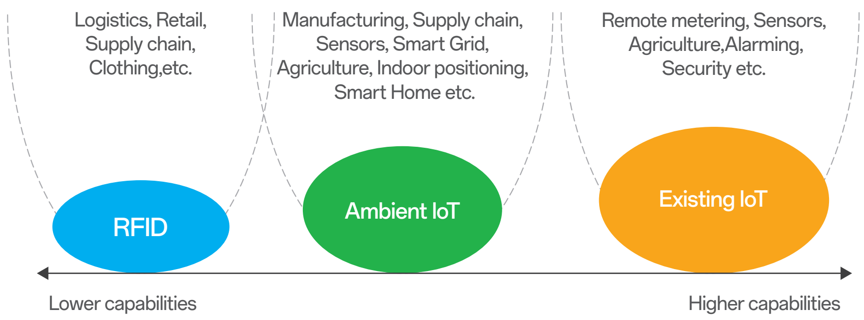

Figure 1.3-1 Technical position of Ambient IoT

Ambient IoT technology is devoted to fulfil abovementioned unsatisfied IoT communication requirements. Ambient IoT is not positioned to replace existing IoT technologies; in contrast it is designed to provide the device and system capabilities which existing IoT technologies cannot provide. Just like Figure 1.3-1 shows, there are clear differentiation between technical abilities of Ambient IoT and those of existing IoT technologies. The scenarios Ambient IoT meets and the corresponding requirements also have little overlap with existing IoT technologies.

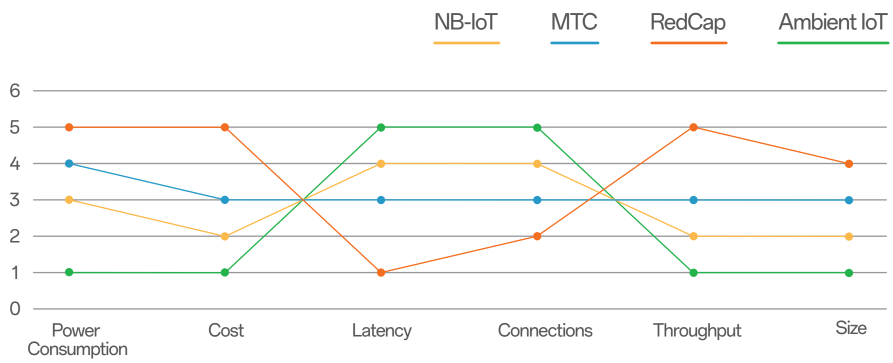

Figure 1.3-2 Comparison of IoT technologies

As shown in Figure 1.3-2, compared with existing technologies such as MTC, NB-IoT and RedCap, Ambient IoT will have significant advantages in terms of device power consumption, size and cost. For example, in term of power consumption, the device power consumption is expected to be reduced from tens of milliwatts of NB-IoT terminals to dozens of microwatts or even several microwatts. In term of cost, the device cost is expected to be reduced from more than ten RMB yuan of the cheapest NB-IoT terminal (lowest among existing technologies) to 1 RMB yuan or even lower. Therefore, with the obvious differences between the above and other technologies, Ambient IoT is expected to become an important candidate technology for the next generation of IoT.

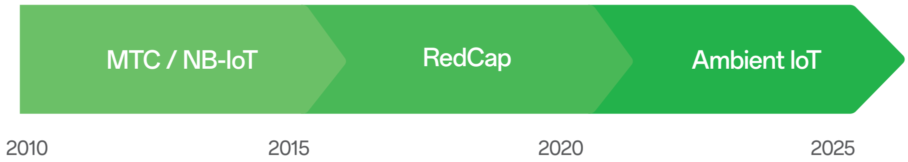

Figure 1.3- 3 Roadmap of IoT technology development

To sum up, Ambient IoT will be committed to meet the communication requirements that existing technologies are still unable to meet and achieve a good complementarity with the existing technologies, so as to meet the multi-level and multi-dimensional communication requirements of IoT.

TYPICAL USE CASES OF AMBIENT IOT

The primary technological advantage of the Ambient IoT is battery-free communication. By utilizing key technologies such as environmental energy harvesting, ultra-low power communication and ultra-low power computing, Ambient IoT terminals can operate without batteries while maintaining minimal hardware complexity. Therefore, the Ambient IoT devices can meet the requirements of extremely low power consumption, small size and extremely low cost. It is foreseeable that Ambient IoT will have significant application advantages in a wide range of fields. For example, applications such as smart manufacturing and industrial monitoring, smart logistics, smart warehousing, smart agriculture, and smart power grid for vertical industries, as well as smart home and indoor positioning for individual consumers. In this section, we will select some typical scenarios to demonstrate the potential applications of Ambient IoT in these fields.

02

2.1 Intelligent manufacturing and industrial monitoring

In the context of Industry 4.0, the aim of intelligent manufacturing and industrial monitoring is to achieve automation and intelligence in the manufacturing process by using new information technologies and manufacturing technologies. More specifically, intelligent manufacturing is a kind of advanced manufacturing method, which integrates intelligent inventory, intelligent classification and intelligent production. Accordingly, industrial monitoring refers to a real-time perception of the production process, production quality, equipment operation and environmental safety, so as to obtain a comprehensive overview of the industrial system. Intelligent manufacturing and industrial monitoring support each other to jointly improve the flexibility, agility and intelligence of manufacturing system such that it is able to cater for the rapidly changing market demands and the highly competitive environments.

In order to meet the requirements of automation and intelligence in the scenario of intelligent manufacturing and industrial monitoring, on the one hand, it is necessary to perform real-time tracking, positioning and recording for the status of materials and products, and on the other hand, it is also important to monitor temperature, humidity, production lines and dangerous events through sensor nodes. In view of the advantages for Ambient IoT devices (i.e., ultra-low power consumption, extremely small size and extremely low cost), Ambient IoT will have a broad prospect in intelligent manufacturing and industrial monitoring. For example, the extremely small and battery-free tags are suitable to be embedded in materials and products to complete inventory and tracking during the process of production and transportation. For another example, industrial sensor nodes in the traditional IoT system may be deployed in harsh environments and special locations, or even in extremely dangerous environments (e.g., high/low temperatures, moving or rotating parts, high vibration conditions, high humidity environments). In these scenarios, legacy battery-based devices may not work well because of the physical and chemical characteristics of the battery. In addition, it may lead to a high cost for network maintenance when using legacy battery-based devices because it is hard or even impossible to replace the battery in these extreme environments. However, Ambient IoT devices can easily fit in these extreme environments due to its batter-free characteristic and ultra-low power consumption. Furthermore, the issue of network maintenance can also be addressed because Ambient IoT devices are energized based on wireless power or environmental energy and do not need to have the battery replaced (i.e., maintenance-free). By the way, most of Ambient IoT devices have very low cost.

Therefore, the application of Ambient IoT technology in intelligent manufacturing and industrial monitoring scenarios can not only achieve the goal of industrial system automation and intelligence, but also reduce the cost of deployment and maintenance while expanding the application scenario.

- Typical scenarios in intelligent manufacturing and industrial monitoring:

In-factory logistics

Containers with integrated Ambient IoT tags are sent to suppliers to load materials. The Ambient IoT tags are activated for inventory when returning to the factory, and hence material information is obtained and recorded in the inventory system. The registered container is then delivered to a designated area within the factory. For a target product, the smart factory automatically generates a pick list. Accordingly, the smart forklift moves to the designated area to obtain materials according to the pick list and inventory system, during which it may be necessary to use the Ambient IoT tag for positioning. Finally, the smart forklift delivers the material to the production process.

Production line monitoring

For products processed on a production line, Ambient IoT tags can also be embedded in these products. With the help of Ambient IoT tags, real-time tracking for the status of the products on the production line can be achieved. For example, it is able to know which process the product is currently located in or which process has been completed, so as to ensure that the product has completed all of required steps before moving to the next step. For another example, Ambient IoT tags can also record the production information of each step, such as the manufacturer and responsible personnel of the step, for subsequent quality traceability.

Environmental information collection

In some special environments (e.g., high temperature, high pressure, extreme cold, radiation), Ambient IoT tags are used to collect environmental information. For example, it can monitor the temperature and humidity information in the data center or equipment room to prevent network service quality from being affected.

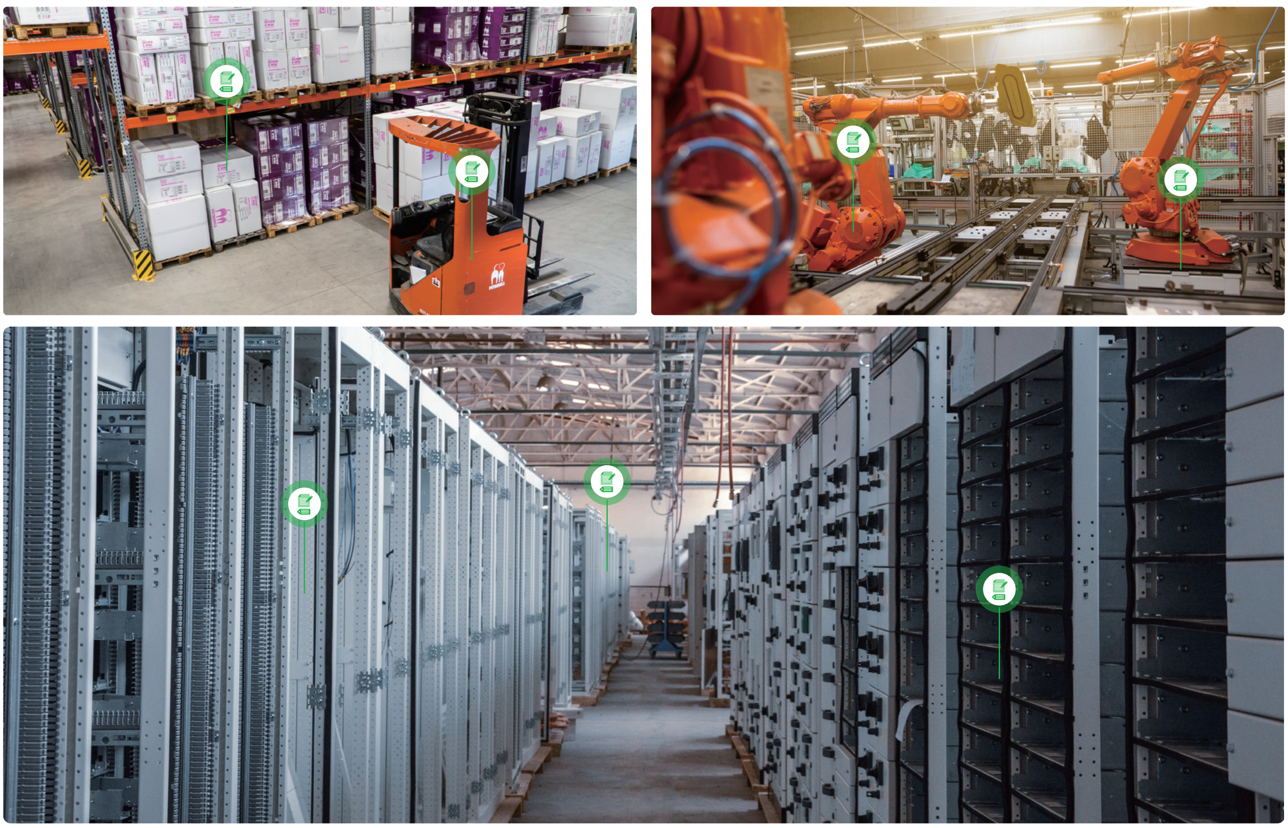

Figure 2.1-1 Examples of Ambient IoT in intelligent manufacturing and industrial monitoring

Typical requirements of intelligent manufacturing and industrial monitoring

Requirements for devices:

In most cases, Ambient IoT devices are electronic tags with integrated memory for data access and/or integrated sensor for information acquisition. Since Ambient IoT devices are usually deployed in a large scale (e.g., each asset or device will be equipped with a tag), the cost and power consumption need to be considered.

Power consumption: lower than 1mW, battery-free, maintenance-free.

Work environment: Work well in special environments (e.g., high temperature, high pressure, extreme cold, radiation).

Size: extremely small size for large scale application.

Coverage: tens of meters to hundreds of meters.

Device Type: paper tag or anti-metal tag.

Requirements for network:

Deployment: Flexible deployment based on network infrastructure. Network equipment can be deployed on outdoor light poles or with digital indoor system to provide fundamental coverage. Additional deployment can be considered for dead zone or coverage enhancement.

Coverage: Single site needs to provide the coverage of >30m for indoor scenario and >100m for outdoor scenario.

Security: Authorization-based reading and writing to protect privacy and data security.

Capacity: Support sufficient system capacity and support a large number of devices to read data.

2.2 Logistics and warehousing

With the sustained and stable development of the economy, the economic volume is getting larger and larger, which is followed by the further expansion of the scale for logistics. Logistics is a very important link in the supply chain of commodity circulation, and occupies an important position in the national economy, and warehousing is the core link of modern logistics.

In logistics and warehousing scenarios, lots of goods need to be frequently transferred, stored, loaded, unloaded and inventoried in logistics stations or warehouses (tens of thousands of square meters). With the occurrence of warehouse ordering, entering warehouse, goods management and leaving warehouse, a large amount of warehousing information will be generated, which has the characteristics of frequent data reading and large quantity.

In order to manage packages/goods digitally and improve the management efficiency of logistics and warehousing, it is usually necessary to paste the identification of terminal on the surface of packages/goods for obtaining logistics information and managing the whole logistics process. Therefore, the small terminal size is more conducive to industry applications. At the same time, the company of express delivery or warehouse suppliers can only accept the very low-cost terminal due to the huge amount of goods, cost performance and competitiveness.

Ambient IoT devices have the characteristics of extremely low cost, small size, maintenance-free, durable, long life and so on. In logistics and warehousing, Ambient IoT devices can be used to record, save and update the information of goods. That is the Ambient IoT based logistics and warehousing system, which is beneficial for reducing costs, significantly improving the efficiency of logistics and warehousing management, and realizing of smart logistics and smart warehousing. In addition, sensors can be integrated with Ambient IoT devices to be used to collect environmental information during the process of transportation and warehousing especially for items such as fresh products that have extremely high requirements for the transportation and storage environment, so as to avoid product decay and deterioration.

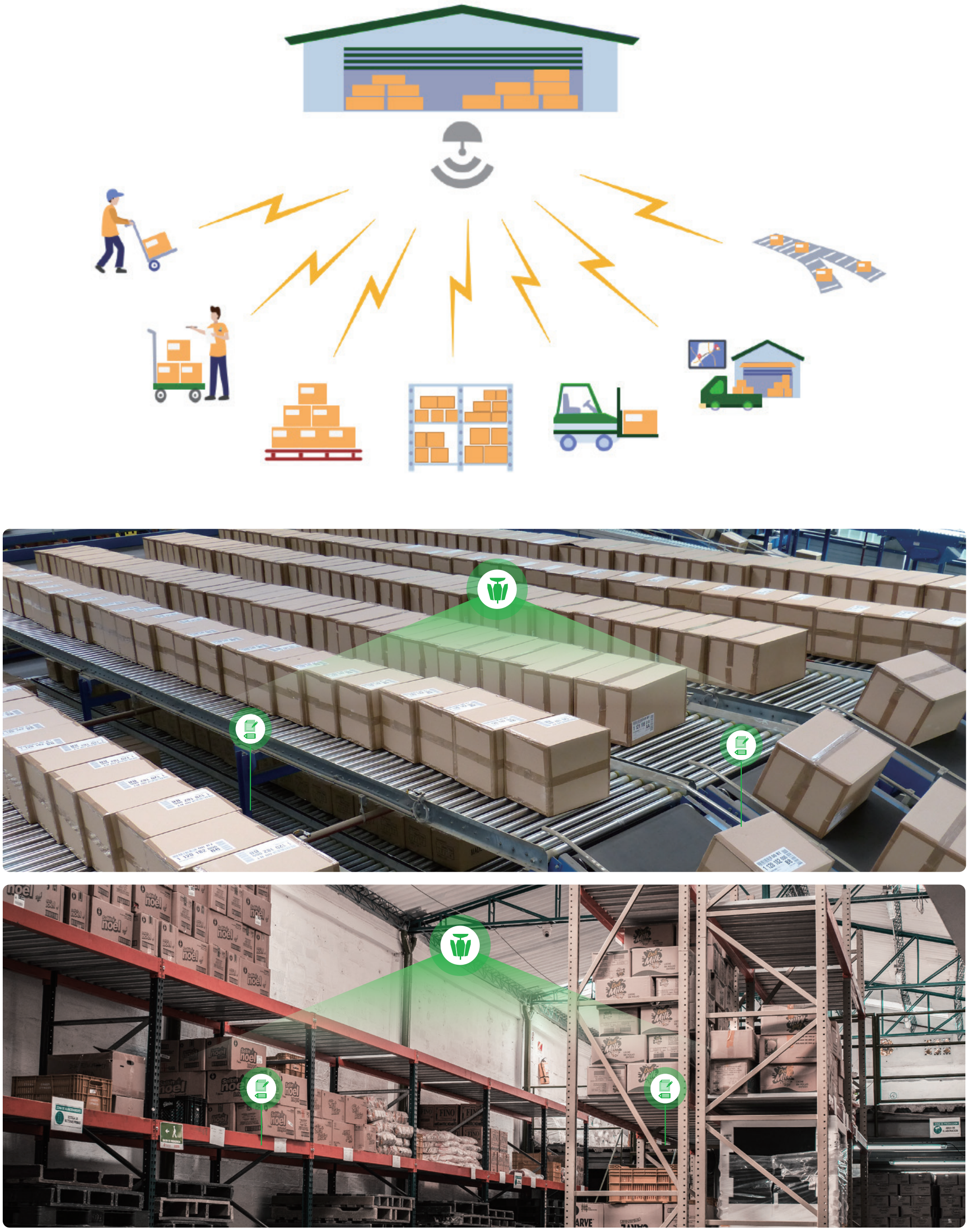

Figure 2.2-1 Ambient IoT devices in smart logistics and smart warehousing

More specifically, Ambient IoT can enable smart logistics and warehousing and improve efficiency and productivity by:

Batch and wide range reading

Ambient IoT tags support large numbers of simultaneous reading and wide range reading. When the goods arrive at a warehouse, the Ambient IoT tags attached to the goods can be read in batch (e.g., thousands of tags per second) to obtain accurate information about the goods, such as size/weight, manufacturer, expiration date, serial number, production line, etc. The Ambient IoT tags attached to the goods or containers in the warehouse will save their basic information and location information. By setting up a central network node in the warehouse, all the goods in the warehouse can be identified in a timely and rapid manner, which is convenient for managers to understand the inventory distribution/total amount of goods and predict the corresponding storage demand.

Transportation management

When the goods with Ambient IoT tags are moving in the warehouse, network equipment can recognize and update the information of tags in time. Furthermore, network equipment is able to obtain the position information of tags [1]. When the corresponding goods need to be picked, the location of the goods can be quickly achieved within the entire warehouse. In this way, the sorting efficiency of the goods is improved significantly.

Cold chain transportation

Ambient IoT tags integrated with sensors are affixed in containers or on the surface of items for cold chain transportation. The Ambient IoT tags are used to monitor the temperature, humidity or product status information in transportation, so as to detect abnormal situations in time and ensure the quality and safety of fresh food.

Figure 2.2-2 Ambient IoT in code chain transportation

Typical requirements of smart logistics and smart warehousing

Requirements for devices:

In most cases, Ambient IoT devices are electronic tags. Since Ambient IoT devices are usually deployed in a large scale (e.g., each asset or device will be pasted with a tag), the cost, size and power consumption need to be considered. For monitoring conditions such as temperature and humidity in transportation or storage through Ambient IoT tags, corresponding integrated sensors are needed.

	Power consumption: battery-free, maintenance-free. **Cost:** extremely low cost due to large scale deployment in warehouse, integrated sensors are needed for environment monitoring. **Size:** extremely small size for large scale application. **Coverage:** tens of meters to hundreds of meters. **Work environment:** Work well in special environments (e.g., high temperature, high pressure, extreme cold).
Requirements for network:	**Deployment:** Flexible deployment based on network infrastructure. Network equipment can be deployed on outdoor light poles or with digital indoor system to provide fundamental coverage. Additional deployment can be considered for dead zone or coverage enhancement. **Coverage:** Single site needs to provide the coverage of >30m for indoor scenario and >100m for outdoor scenario. **Security:** Authorization-based reading and writing to protect privacy and data security. **Capacity:** Support sufficient system capacity and support a large number of devices to read data (e.g., thousands of tags per second).

2.3 Smart home

Smart home takes the house as the platform, connects various devices in the home through the Internet of things to build an efficient livable system. Smart home uses automatic control of household appliances, lighting control, temperature control, anti-theft and alarm control and other functions and makes the home environment safer, more convenient and comfortable.

Ambient IoT can achieve battery-free (i.e., no need to charge), hence it can greatly increase the life of the corresponding equipment in smart home and reduce maintenance costs. At the same time, it can be deployed very flexible in smart home, such as embedded in walls, ceilings and furniture, or affixed to keys, passports, clothes, shoes due to its ultra-low cost, extremely small size, washable, flexible/foldable and other characteristics [2]. Based on the above advantages, Ambient IoT can expand the application of smart home scenarios, and has great potential in the field of smart home.

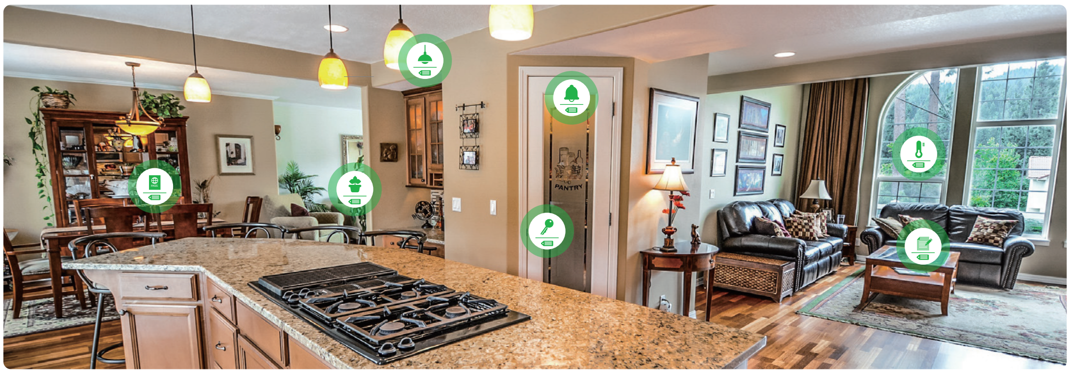

Figure 2.3-1 Ambient IoT in smart home

- Typical scenarios in smart home:

Item Finding	A small, washable, flexible and foldable Ambient IoT device can be attached to some easily lost items in the home, such as keys, passports, bank cards, wallets, etc. When you need to find these items, you can quickly locate and find the lost items.
Environment monitoring and alarm	Sensors can be integrated with Ambient IoT devices to monitor the temperature and humidity of the house, and can also be used for emergency situations such as gas leaks. The battery-free characteristic of Ambient IoT devices can increase the life of the equipment and achieve maintenance-free;
Intelligent control	Sensors can be integrated with Ambient IoT devices to achieve intelligent control of home devices. For example, automatic control of washing machines, air conditioners, televisions and curtains are executed based on the information collected by the sensor. It is also possible to navigate home robots with tags embedded/attached to doors or furniture and provide more refined control [3].

- Typical requirements of smart home:

Requirements for devices:

In most cases, Ambient IoT devices are electronic tags with integrated memory for data access and/or integrated sensor for information acquisition. In smart home, the cost, power consumption, size, waterproofness and foldability of Ambient IoT devices ought to be considered.

Power consumption: battery-free, maintenance-free.

Delay: tens of milliseconds to hundreds of milliseconds for intelligent control, hundreds of milliseconds to thousands of milliseconds for indoor positioning.

Device Type: paper tag, anti-metal tag, foldable tag or washable tag.

Size: extremely small size for smart home application.

Coverage: tens of meters for indoor scenario.

Requirements for network:

Deployment: Smart terminal can be used as gateway or Ambient IoT devices connect to base station directly.

Coverage: 10-30m for indoor scenario.

Security: Authorization-based reading and writing to protect privacy and data security.

Number of connections: tens to hundreds.

Power charging: The existing wireless equipment (e.g., smart phone, CPE, AP) can be regarded as the source of power. In this case, no additional equipment for power supply is needed.

2.4 Indoor positioning

At present, the outdoor positioning technology is maturing rapidly, and GPS positioning or cellular positioning technology has well met the positioning and navigation requirements in people's daily life. However, in regard to the increasing demand for indoor positioning and navigation, there is still a lack of effective and low-cost technical solutions. For example, in daily life, shopping is one of the indispensable activities for people. Large global shopping centers are constantly emerging, however, it is often difficult for people to find target shops and restaurants quickly in such large shopping malls. Another example is the underground parking, where people often can't find free parking spaces in time and their tourism experience can be significantly diminished. In order to solve these problems, we can provide indoor positioning and navigation services with the help of Ambient IoT technology, helping customers find the required information and target places more efficiently.

Ambient IoT technology harvests the energy in the surrounding environment, such as light, heat or RF signals, to enable devices that do not require batteries or use only capacitors to work for a decade or even longer time. This technology is maintenance-free, low complexity, lightweight, and low cost, making it ideal for high-density deployments.

Take a 200,000 m^2 shopping mall as an example. It consists of one or more buildings with multiple floors above and below ground, and the underground parking lot has hundreds to thousands of parking spaces. In order to meet the indoor positioning accuracy requirements, indoor positioning and navigation systems can be deployed in such shopping centers. Specifically, we can distribute reference tags in a high-density, uniform manner on every floor and in every room of the shopping center, for example, deploying one tag every 2 meters. In this way, indoor positioning can be realized on handheld devices (such as smart mobile phone). These handheld devices can communicate with reference tags to provide users with accurate navigation and positioning services.

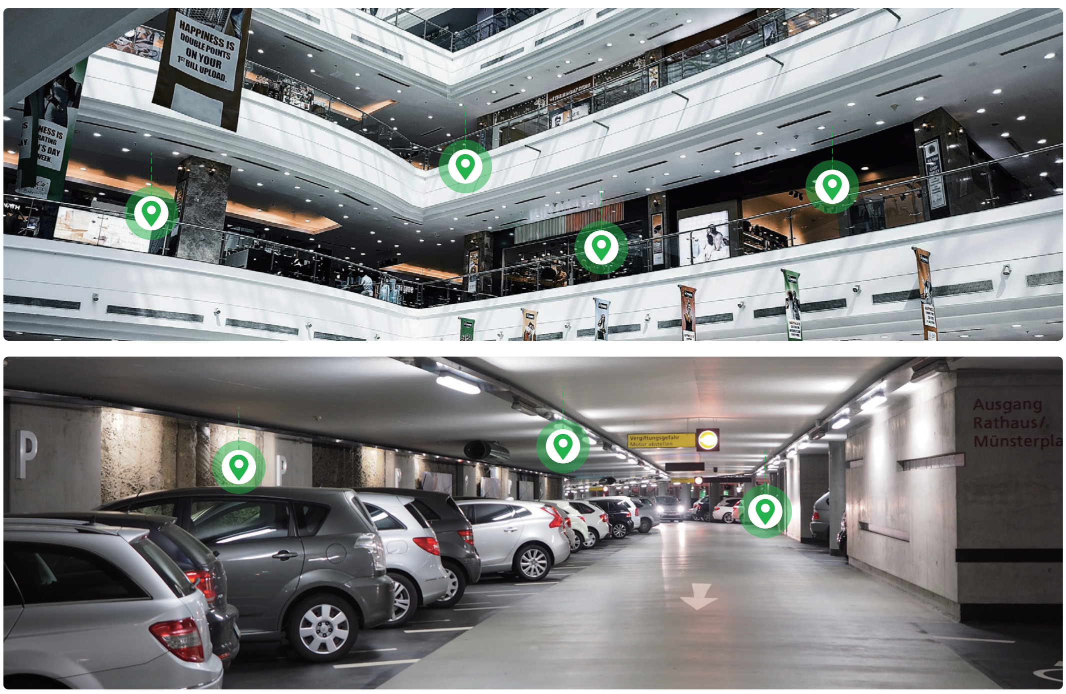

Fig. 2.4-1 Application of Ambient IoT technology in indoor positioning

In addition, this indoor positioning and navigation system is not only widely used in shopping centers, but also in many other application scenarios. In the field of intelligent manufacturing, this system can help to accurately locate the products on the production line or delivery system and accurately grasp the production stage of the products. In the industrial field, for those dangerous areas containing toxic and harmful substances to workers' health, the system can be used to monitor workers' positions in real time by attaching tags to workers, and immediately issue safety alarms when they enter dangerous areas to ensure workers' safety. In addition, in terms of logistics and warehouse management, the system can also be used for inventory and attendance inspection to help managers quickly locate items or persons and improve management efficiency.

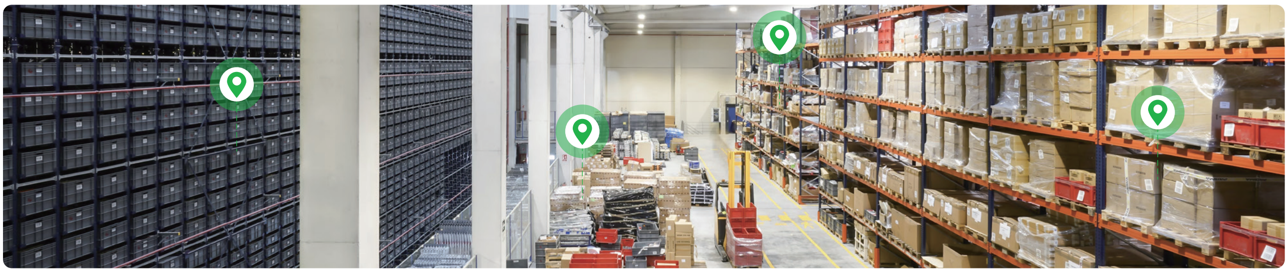

Fig. 2.4-2 Indoor positioning in smart manufacturing and warehousing

In general, the indoor positioning and navigation system based on Ambient IoT technology has a wide application prospect and huge market potential. It will bring more convenient and intelligent experience to our life and work, and become one of the important trends in future.

- Typical use cases for Indoor Positioning based on Ambient IoT technology are as follows:

Underground parking navigation	In each parking space, wall or ceiling of garage， one or more Ambient IoT tags can be deployed as reference anchor points to build an underground parking positioning and navigation system. Users can obtain more accurate positioning and navigation services via handheld devices (such as smart mobile phone).
Shopping mall navigation	one or more Ambient IoT tags can be deployed in interior walls of each store in the shopping mall, and these tags can be used as anchor points for auxiliary positioning to construct the indoor positioning and navigation system. Users can select their targeting stores in this system, obtain accurate positioning and navigation services, and find the target location efficiently. In addition, the Ambient IoT tags can push advertisements or promotional information of merchants to the customers, which enhances people's shopping experiences.
Manufacturing and Logistics	Ambient IoT tags can be attached to products on production lines or delivery systems to locate items for easy management. When goods are in transit, storage, loading / unloading and inventory, the Ambient IoT tags can be attached to the cargo package to provide real-time location information to help track the location and movement of goods.

- Typical requirements of Indoor positioning

Terminal requirements:

The form of an Ambient IoT device can be an electronic tag. When constructing the positioning system, the number of Ambient IoT devices required is relatively large, which should have the characteristics of maintenance-free, low complexity, portability and low cost.

Tag power consumption: Battery free, no battery replacement, charging and other related maintenance issues.

Tag type: Paper tag or anti-metal tag.

Tag Size: Extremely small size.

Tag Price: Extremely low cost, suitable for high-density deployment;

Network requirements:

Coverage requirements : 10m to 30m.

Positioning accuracy : horizontal accuracy 1-3 meters.

Energy Harvesting signal : The smart device carried by the user is used as the transmitting device of the energy harvesting signal for the Ambient IoT tags. No additional energy harvesting signal is needed and the network layout is simplified. Meanwhile, dedicated nodes for assisted energy supply can be deployed.

Network security: Authorization-based tag reading for privacy and data security.

2.5 Smart grid

With around 80 million kilometers of transmission and distribution lines worldwide, electricity networks are the backbone of secure and reliable power systems. As stated in the World Energy Outlook 2020 [4], significant investment takes place in new network capacity between 2019 and 2030 as a result of growing demand for electricity, the addition of new renewable generation capacity and the need to develop smart grids. The expansion of electricity networks to 2030 is about 80% more over the past decade. Around 30% of the increase in transmission lines and 20% of the increase in distribution network lines are attributable to the increase of renewables. Over the next ten years, around 16 million km of existing distribution lines and 1.5 million km of transmission lines need to be replaced or digitalized, together with switching equipment, transformers, meters and other crucial components. In regions with older power systems, such as the United States and the European Union, roughly one-fifth of current networks need to be replaced or digitalized; this corresponds to 2.7 million km in the United States and 3.7 million km in the European Union. More than 60% of global line replacements and new lines are in emerging market and developing economies, with China alone accounting for a third of what is needed (over 7 million km).

Smart grids with wide use of IoT devices have a vital role to play in supporting the penetration of variable renewables electricity sources. IoT has great potential in a wide number of applications in the energy sector, i.e., in energy supply, transmission and distribution, and demand [5]. In particular substations are a significant part of the electrical power grid. Through these stations, the voltage level is converted from high voltage to low voltage using transformer. The substation transfers power to distribution stations by the transmission lines (see Figure 2.5-1). Monitoring electrical substations are necessary to detect faults and resolve them, because if left unattended, it may lead to electrical problems and cause long-term consequences. These problems not only cause energy losses but also lead to electrical outages and losses in expensive equipment, in addition to injuries and accidents such as fire. Therefore, monitoring of substations and their equipment is important to ensure safety, protection, and stability in the electric power networks. Different types of sensors (e.g. temperature and humidity sensors) can be used in the outdoor ultra-high voltage substation (see Figure 2.5-2) to detect the anomaly and trigger predictive maintenance. In addition, various sensors can be used in other use cases in the power transmission and distribution networks (see Figure 2.5-3/4/5) for remote monitoring and protection purposes [6].

For these use cases, the data acquisition process is typically not latency-critical, but a large number of sensors have to be efficiently connected, especially considering many of these sensors have limited power sources and relatively frequent data transmission (every 5-15 minutes) is expected in some cases. Moreover, lifespans of the field IoT devices are expected to be one decade or longer, which is one of the main differences compared with consumer products. Many production systems are subject to regulatory approvals (e.g., safety certification), changes to a running production system often need to be avoided. Often sensors are deployed in locations that are inaccessible, where physical replacement would be unduly expensive. Research continues to develop efficient communication techniques to meet the requirements, among which Ambient IoT [7] is very promising to enable wireless communication with minimum energy consumption. The Ambient IoT devices typically are battery-less or with limited energy storage capability, and obtain energy from the environment. The communication power consumption of such Ambient IoT devices is expected to be a few hundred μW [8][9][10][11]. Moreover, communication service availability with sufficient 5G coverage is important especially for remote monitoring of the critical equipment.

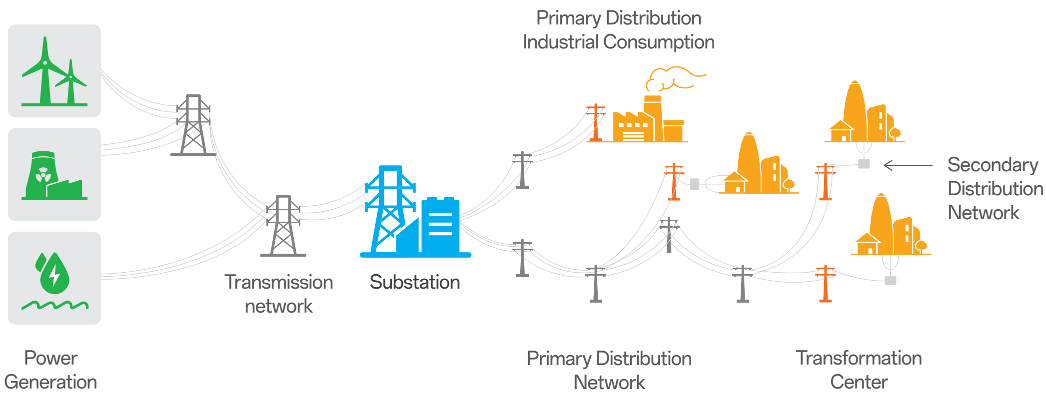

Figure 2.5-1 Smart grid overview

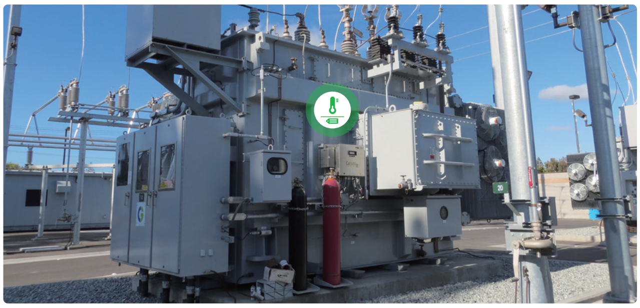

Figure 2.5-2 Outdoor ultra-high voltage substation

Figure 2.5-3 Indoor/outdoor shielding cabinet

Figure 2.5-4 Underground transmission and distribution lines

Figure 2.5-5 Aerial transmission and distribution lines

- Typical use cases for Smart Grid based on the Ambient IoT technology are as follows:

Monitoring of high-voltage transmission line	Problems such as electric leakage and tilt of transmission tower can be detected by monitoring high-voltage transmission line.
Substation equipment inspection	Using temperature sensors to detect whether the temperature of substation equipment is abnormal, preventing accidents such as equipment aging and short circuits.
Asset inventory of power plant equipment	Through communication with Ambient IoT tags on power plant equipment, asset inventory of power plant equipment can be realized in a completely contactless way.

- Typical requirements for Smart Grid based on the Ambient IoT technology are as follows:

Terminal requirements:

Tag power consumption: Battery free, no battery replacement, charging and other related maintenance issues.

Communication delay: Smart Sensor Data Acquisition, Second Level.

Tag type: Paper tag or anti-metal tag.

Tag Size: Extremely small size for large scale applications.

Communication distance: 10 ~ 30m indoors or 50 ~ 200m outdoors.

Connection number: Support thousands to tens of thousands of device connections per square kilometer

Network requirements:	**Flexible deployment：** Use intelligent terminal as gateway device or directly connect with base station. **Coverage requirements:** indoor 10 ~ 30m and outdoor 50 ~ 200m. **Network security:** Authorization-based tag reading for privacy and data security. **Connection requirements：** Support sufficient system capacity and data reading of a large number of terminals

2.6 Smart agriculture

Ambient IoT devices can be used in smart agriculture to monitor the environment and control the facilities such as the irrigation system.

A smart greenhouse for tomato planting is built in a farm. Some sensing Ambient IoT devices are placed in the smart greenhouse to monitor the air temperature and humidity, carbon dioxide concentration, light, soil temperature, humidity and PH. Some operation Ambient IoT devices are placed in the smart greenhouse to control the window and irrigation system. A pico cell or a reader UE (with subscription of Operator) is placed in the smart greenhouse to communicate with the Ambient IoT devices.

These Ambient IoT devices power themselves by harvesting energy from the environment (e.g. solar, RF energy). The maximum power consumption for Ambient IoT device could be limited (e.g. several hundred micro-watts) [9][10][11].

Considering the greenhouse environmental control, crop growth characteristics and economic benefits, the optimal scale of greenhouse construction is 8 ~10 meters span, 80~100 meters length. The size of the greenhouse could be very huge, it is reported recently that a single greenhouse area reaches nearly 70,000 square meters, equivalent to ten standard football field size. To provide all-round technical support for a greenhouse of nearly 70,000 square meters, a "super brain" is needed. This computer monitors tens of thousands of sensors in the greenhouse, people can sit in front of the computer and know everything going on in the greenhouse. For example, the temperature and humidity in each area of the 70,000 square meters greenhouse, the temperature of the underground heating tube, how much the concentration of carbon dioxide is, whether the fan is opened, and whether the nutrition is enough for each tomato.

Figure 2.6-1 A picture for huge greenhouse

- Typical use cases for Smart Agriculture based on the Ambient IoT technology are as follows:

Soil moisture monitoring	Controls whether the intelligent irrigation system increases or decreases the amount of watering by monitoring the soil moisture.
Air temperature, humidity and carbon dioxide monitoring	Control opening or closing of greenhouse ventilation pipes or control opening or closing of greenhouse windows by monitoring temperature, humidity and carbon dioxide concentration in the greenhouse.
Agricultural facility control	Based on the monitoring results, Ambient IoT can be used to control agricultural facilities for operations such as watering, fertilizing, and ventilation.

- Typical requirements for Smart Agriculture based on the Ambient IoT technology are as follows:

Terminal requirements:

Tag power consumption: Battery free, no battery replacement, charging and other related maintenance issues.

Communication delay: Smart Sensor Data Acquisition, less than 1 second.

Tag type: Paper tag or anti-metal tag.

Tag Size: Extremely small size for large scale applications.

Communication distance: Up to 30m indoors.

Connection number: Support one device connection per square meter; Process thousands to tens of thousands of devices per second by reading device ID information.

Network requirements:

Flexible deployment: Use intelligent terminals as gateway devices or directly connect with base stations.

Coverage requirements: indoor 30m.

Network security: Authorization-based tag reading for privacy and data security.

Connection requirements: Support sufficient system capacity and data reading of a large number of terminals.

2.7 References

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TECHNICAL PRINCIPLES OF AMBIENT IOT COMMUNICATION

Ambient power enabled IoT devices should be mainly able of energy harvesting, ultra-low power consumption of communication and computing, as shown in Figure 3-1, so as to achieve the advantages of battery-free and maintenance-free. Due to the low energy density of ambient power, the energy collected by ambient IoT devices is very limited. Therefore, ultra-low power communication and computing technology are essential to transmit, receive and process data. Additionally, ultra-low power communication technology at least includes backscattering, ultra-low power transmission, ultra-low power reception.

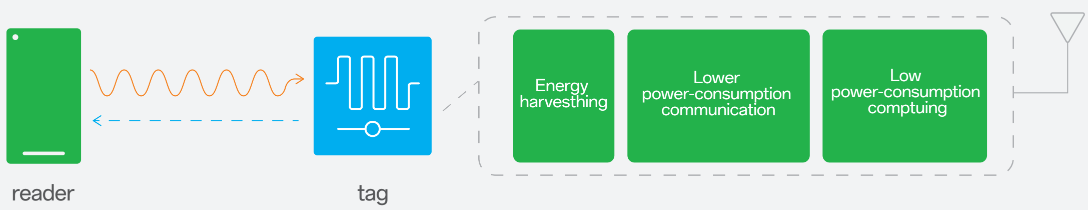

Figure 3-1 The technical schematic of Ambient power enabled IoT communication

03

3.1 Ambient energy harvesting and storage

For ambient IoT devices, energy can be harvested from different types of ambient power sources. Ambient power includes radio waves, solar energy/light, thermal energy, mechanical vibration, airflow and acoustic noise, etc.

3.1.1 Ambient energy harvesting

RF energy

One of the most important functions of power harvesting is to collect electromagnetic waves and convert radio frequency energy into direct current (RF-DC). In Ambient IoT communication, the collected energy is used to drive the load circuit (low-power computing, sensors, etc.) to achieve battery-less communication.

Due to its controllable energy output and availability (e.g., RF transmitters can send power on demand or at regular intervals), RF-based energy harvesting used to apply to logistics/warehousing, manufacturing, smart home, health monitoring, etc.

There are several challenges regarding RF power harvesting.

1) It is difficult to collect RF energy in a wireless environment due to the low power density (e.g., less than 10nW/cm^2). The RF power that can be effectively collected shall exceed a certain input power threshold, which can be called as RF power harvesting sensitivity of such device.

2) In order to drive logic circuits or chips, DC voltage converted from RF energy shall meet the minimum output voltage requirements. It remains a big challenge to efficiently convert RF to DC under the condition of very low input power.

3) Intelligently managing the collected or stored energy is also important for a good balance of communication and computing.

Currently, it shows by results from experimental researches that the RF energy conversion efficiency is different for different input power and energy harvesting circuit designs. For example, the energy conversion efficiency at input power of -20dBm is often less than 10% while the conversion efficiency at input power of -1dBm is close to 50%. When input power is less than -30dBm it is very challenging to effectively collect RF energy and rectify it into a usable DC voltage.

Generally, the power required to drive ultra-low power circuit is at least 10uw. In order to meet requirements of the basic low-power computing and communication, it can be seen that improving the efficiency of energy collection and conversion under the condition of low input power is one of the most important tasks in the research and development of ambient-power enabled IoT communication system [1].

Table 3.1-1 Input power vs. RF energy conversion efficiency [1]

Efficiency (%)	Input power (dBm)	Center frequency (MHz)	Reflector unit
1.2	-14	950	0.3-µm CMOS convertor
5.1	-14.1	920	0.18-µm CMOS convertor
10	-22.6	906	0.25-µm CMOS convertor
11	-14	915	90-µm CMOS convertor
12.8	-19.5	900	0.18-µm CMOS , $CoSi_2$ - Si Schottky
13	-14.7	900	0.35-µm CMOS convertor
16.4	-9	963	0.35-µm CMOS convertor
18	-19	869	0.5-µm CMOS convertor
26.5	-11.1	900	0.18-µm CMOS convertor
36.6	-6	963	0.35-µm CMOS convertor
47	-8	915	0.18-µm CMOS convertor
49	-1	900	Skyworks SMS7630 Si Schottky

The research of power harvesting circuits has gone through many years of development and exploration, improving efficiency has always been the most concerned issue in circuit design. For RF-DC conversion, the circuit designs have obvious impact on the efficiency. The proper use of the rectifier can well convert the radio frequency energy into a stable direct current voltage (RF-DC). If the output voltage is low, further direct current conversion boost (DC-DC) is required. Voltage regulators and voltage monitors are also commonly used to help boost and stabilize the output voltage. Diode-based rectifier circuits are the most basic method for energy harvesting. And CMOS-based devices that usually requires input power less than -20dBm can have better performance than discrete devices.

The typical power harvesting circuits include half-wave rectifier (as shown in Figure 3.1-1), single shunt rectenna, single stage voltage multiplier (as shown in Figure 3.1-2), Cockcroft-walton/Greinacher charge pump, Dickson charge pump, modified Cockcroft-walton/greinacher charge pump).

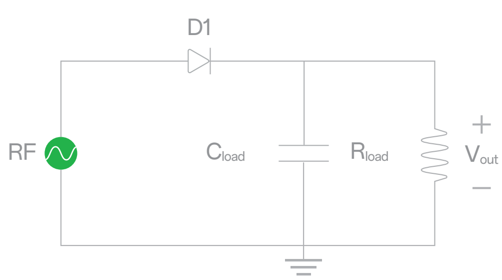

Figure 3.1-1 Half-wave rectifier

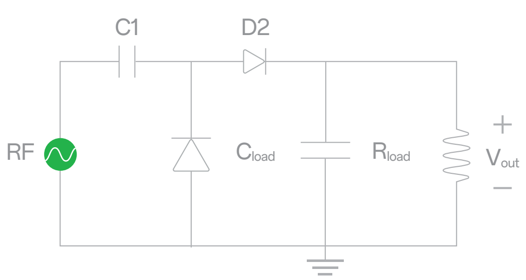

Figure 3.1-2 Single stage voltage multiplier

Solar Energy /Light

Solar power/light can be transformed into electrical power using photovoltaic cells and it uses photovoltaic effect for energy harvesting with conversion efficiency of 10-40% [2] . For the outdoor case, solar energy is one of the most common ambient power, it can supply inexhaustible clean energy and has high power density of up to 100 mW/cm^2 [3] .

Solar power is unstable, inconsistent, and intermittent. It is highly dependent on the atmospheric condition, surrounding obstructions, etc. It is available during daytime but inefficient on a cloudy day or during the night. Solar energy harvesting can be mainly used for outdoor environmental monitoring, agriculture, husbandry, transportation, etc. For the indoor cases, light from the lighting equipment can be used. Although the power density is lower than solar, e.g., 100uw/cm^2, it is much stable and controllable. Energy harvested from light can be used for manufacturing, indoor environmental monitoring etc.

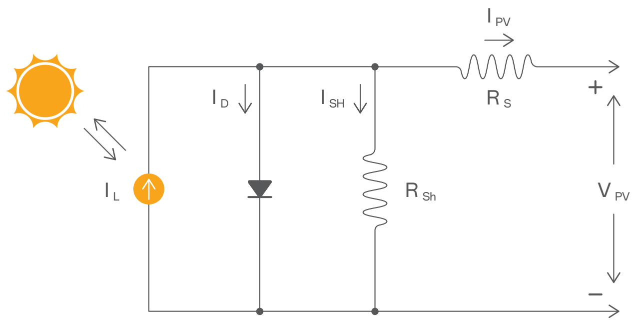

Figure 3.1-3: The equivalent electrical circuit of a single diode solar PV cell [4]

Thermal Energy

Thermal energy is another ambient power source that are available for lots of use cases. Electrical power is directly generated by exploiting the temperature difference in thermoelectric devices taking advantage of thermoelectric effects, such as the Seebeck effect or the Thomson effect. Thermoelectric generators have low efficiency (only about 5-6%) [5] . The power density is 25~1000uw/cm^2 depending the environment condition.

Although with low conversion efficiency, thermal energy can be used in many outdoor applications or indoor cases as long as temperature difference or temperature fluctuation can be expected in the environment. For example, outdoor environmental monitoring, smart grid, agriculture, husbandry etc.

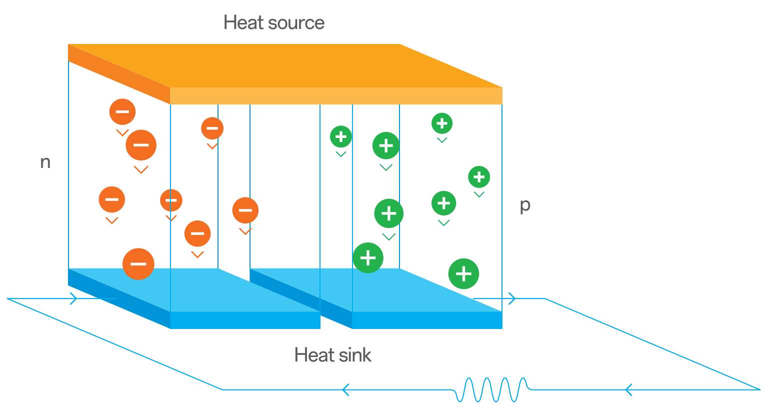

Figure 3.1-4: Seebeck effect

Mechanical Vibration

The piezoelectric effect generates electrical voltages or currents from mechanical strains, such as vibration or deformation. Typical piezoelectric-based energy harvesters keep creating power when there is a continuous mechanical motion, such as acoustic noises and wind, or they sporadically generate power for intermittent strains, such as human motion (walking, clicking a button, etc.). The volume of the piezoelectric power generators is relatively small and typical output power density values of usual piezoelectric materials are around 250 μW/cm^3 but they can create more power when a motion or deformation is intense [6][7].

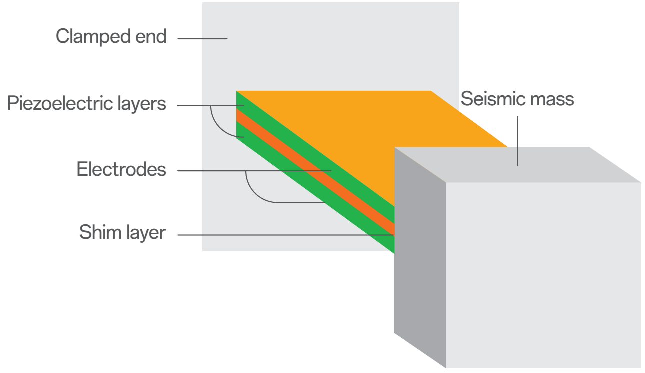

Figure 3.1-5: Piezoelectric energy harvesting generator [8]

From the discussion above, it can be seen that kinds of ambient power have the following characteristics:

For typical ambient power, it can be observed the power harvested is very limited, e.g. from 1uW to 100mW (per cm^2/cm^3).

For some ambient power from artificial power source (e.g., light, RF waves), the power can be stable and constant. But for some other kind of ambient power such as solar, heat or vibration, the ambient power will be unstable (intermittent, not constant). It is impossible to use the ambient power as a direct power source for electronic devices.

Table 3.1-2 the comparation of energy sources

Energy source	Type	Typical power	Note
Outdoor solar light	Natural	100 mW/cm^2 (outdoor)	Uncontrollable but predictable
Indoor office light	Artificial/natural	100 μW/cm^2 (artificial light) 10 mW/cm^2 (filtered solar light)	Partially controllable
Ambient radio frequency	Artificial	0.1 μW/cm^2 -10 μW/cm^2	Controllable and predictable
	Artificial/natural	0.001 μW/cm^2 (WiFi) 0.1 μW/cm^2 (GSM)	Uncontrollable and unpredictable
Thermoelectric	Artificial	60 μW/cm^2	Partially controllable
Vibration	Artificial	4 μW/cm^3 (human motion) 800 μW/cm^3 (machines)	Uncontrollable but predictablz
Ambient airflow	Natural/artificial	1 mW/cm^2	Uncontrollable and unpredictable
Acoustic noise	Natural/artificial	960 nW/cm^3	Uncontrollable and unpredictable

3.1.2 Ambient energy storage

Based on the analysis in the previous sections, it can be seen that at least for some ambient IoT devices, energy storage components are required due to the followings:

- The energy storage component can stabilize and control the power output, and can smooth the power fluctuations of the collected ambient energy through peak shaving and valley filling.
- It is able to collect weak harvested power (e.g., microampere or even nanoampere level) and provide higher peak discharge current (e.g., tens of microampere to hundreds of microampere level) for the ambient IoT devices.

There are many types of storage components suitable for ambient energy IoT devices, e.g., capacitors and supercapacitors. Energy storage components make more types of ambient energy possible for ambient energy IoT devices.

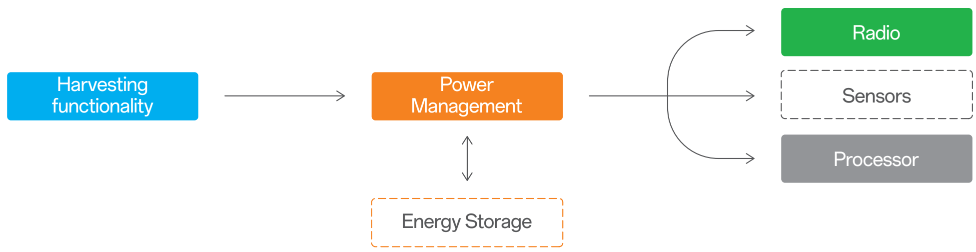

Figure 3.1-6 One example of Ambient IoT device Implementation

Capacitor can be considered as the basic energy storage elements for ambient IoT devices, in case that power sources are stable and constant. Capacitor have limited power perseverance time and storage capacity, which can restrict the ambient IoT application. For example, with a fully charged capacitor of 24uF, it can drive the ambient IoT devices for 3.6k bits communication (1.5V, 10uA and 1kbit/s are assumed).

Printed solid-state batteries offer durability and higher capacity, making them a great additional storage option. Taking a 1μAh, 1.5V solid-state battery as an example, it can even drive surrounding IoT devices for 360kbit communication (assuming a circuit voltage of 1.5V and a current of 10μA).

When selecting energy storage components for ambient IoT devices, it is necessary to comprehensively consider the two aspects of "source" and "consumption" in the real use case, at least including the energy collection status, the consumption requirements of communication, computing, sensor and other components of the device., etc. Since different data rates and Tx powers are required for ambient IoT devices, the transitions between different operating modes such as energy harvesting, dormant state or active state, are also very important.

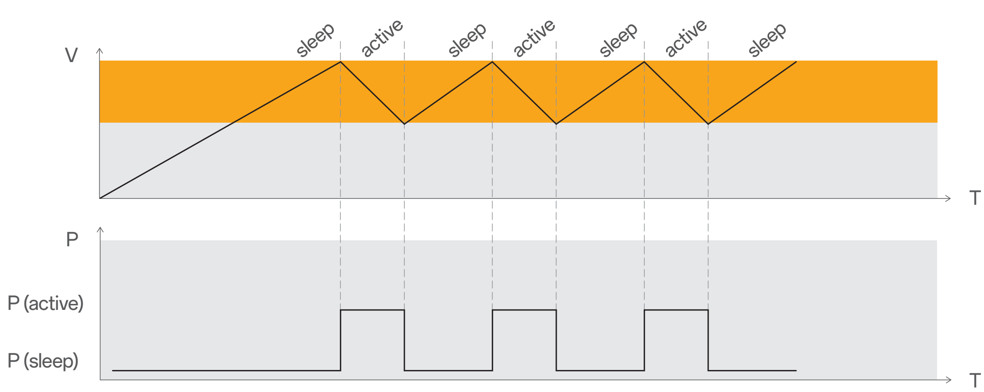

Figure 3.1-7 Examples of different operating modes for ambient IoT devices

3.2 Ultra-low power communication

3.2.1 Backscatter transmitter

The backscatter technology enables signal transmission without an active transmitter. Similar as radar technology, a part of electromagnetic waves will be reflected when they reach the surface of an object. The strength of the reflected signal depends on the shape, material and distance to the object. From the perspective of a radar, each object has its radar cross section (RCS) [9]. A tag achieves signal modulation by changing its backscatter factor, which is equivalent to its RCS. The backscatter transmitter modulates the reflected RF signal to transmit data without generating the radio-frequency (RF) signal itself.

Backscatter was first proposed by Stockman in 1948 [10]. However, traditional backscatter communication cannot be widely used in data-intensive wireless communication systems due to the following limitations.

1)Traditional backscatter communication requires the placement of the backscatter transmitter near its RF source, thereby limiting the use and coverage area of the device.

2)In traditional backscatter communication, the receiver of the backscattered signal and the RF signal transmitter are located in the same device, i.e., the reader, which results in self-interference between the receiving and transmitting antennas, thereby degrading communication performance.

3)A backscatter transmitter passively responds only when inquired by a reader.

Recently, Ambient Backscatter Communication (AmBC) [11] has become a more promising technology for low-power communication. It can effectively address the aforementioned limitations in traditional backscatter communication systems, making AmBC technology more widely adopted in practical applications.

The AmBC system typically consists of three parts: the ambient RF source, the backscatter device (BD), and the reader. In AmBC systems, backscatter devices can communicate with each other by utilizing wireless signals broadcast by ambient RF sources such as TV towers, FM towers, cellular base stations, and Wi-Fi access points (APs). By separating the carrier transmitter and the backscatter receiver, the number of RF components in the backscatter device is minimized. Furthermore, the backscatter device can operate actively, i.e., the backscatter transmitter can send data without the trigger of a reader when it has harvested sufficient energy from the RF source.

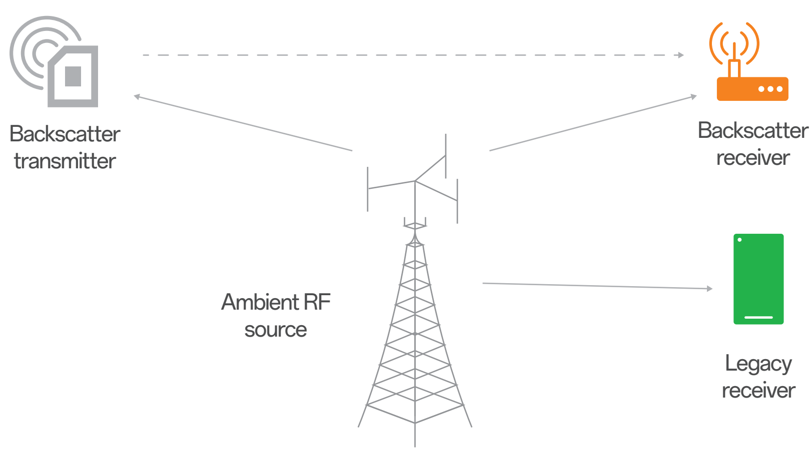

Figure 3.2-1 Illustration of AmBC system [12]

In a typical backscatter communication process, Ambient IoT devices (such as backscatter tags) receive carrier signals sent by readers and harvest energy through RF energy harvesting modules, which is used to power the low-power processing modules. After obtaining energy, the backscatter tags drive corresponding circuits to modulate incoming signals and perform backscattering.

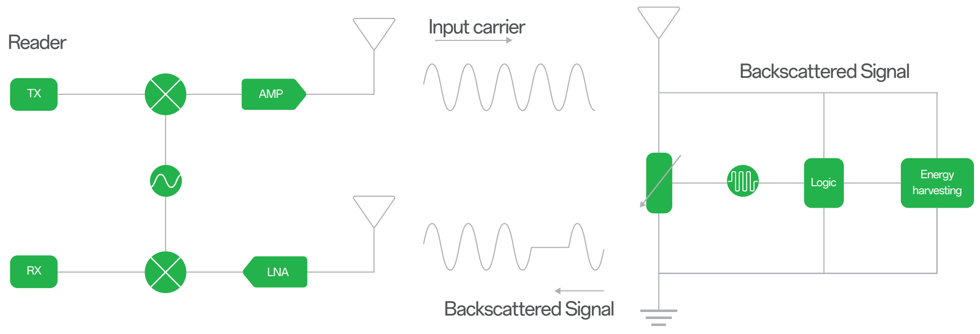

Figure 3.2-2 Backscattering communication

In the backscatter communication system, load modulation is a common method used by tags to transmit data. Load modulation adjusts the electrical parameters (such as resistance or capacitance) of the tag's oscillating circuit according to the data stream, thereby changing the size and phase of the tag's impedance, completing the modulation process.

There are two main types of load modulation techniques: resistive load modulation and capacitive load modulation. In resistive load modulation, a resistor is connected in parallel with the load, called the load modulation resistor. This resistor is turned on and off according to the clock of the data stream, and the switch S is controlled by binary data encoding. In capacitive load modulation, a capacitor is connected in parallel with the load instead of the load modulation resistor controlled by binary data encoding.

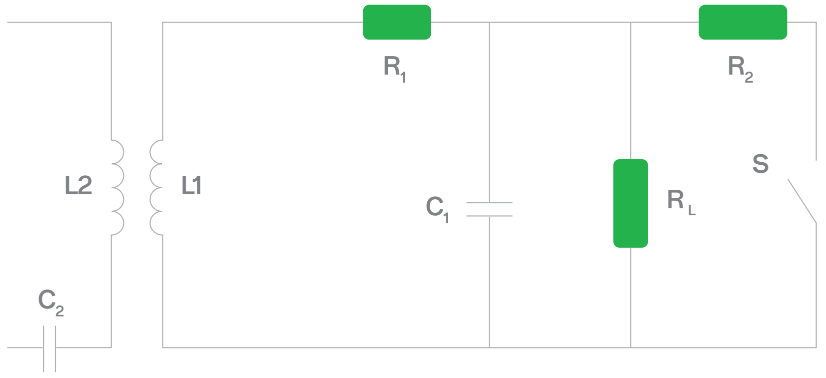

Figure 3.2-3 Resistance-based modulation

Taking resistance-based ASK modulation as an example, the terminal can switch between absorption state and reflection state by adjusting the load reflection coefficient. In the absorption state, the terminal achieves impedance matching thus the input RF signal is completely absorbed by the terminal. Hence, the signal received by the reader will be at low-level, which indicates a bit '0'. On the contrary, in the reflection state, the terminal adjusts the circuit impedance that leads to a mismatch of the impedance thus a part of the RF signal is reflected. Then the signal received by the reader will be at high-level, indicating a bit '1'.

As shown in Figure 3.2-4, the terminal can implement ASK modulation in a simple way of impedance switching. From the perspective of the receiver, ASK signals can be detected with low-complexity envelope detector and comparator.

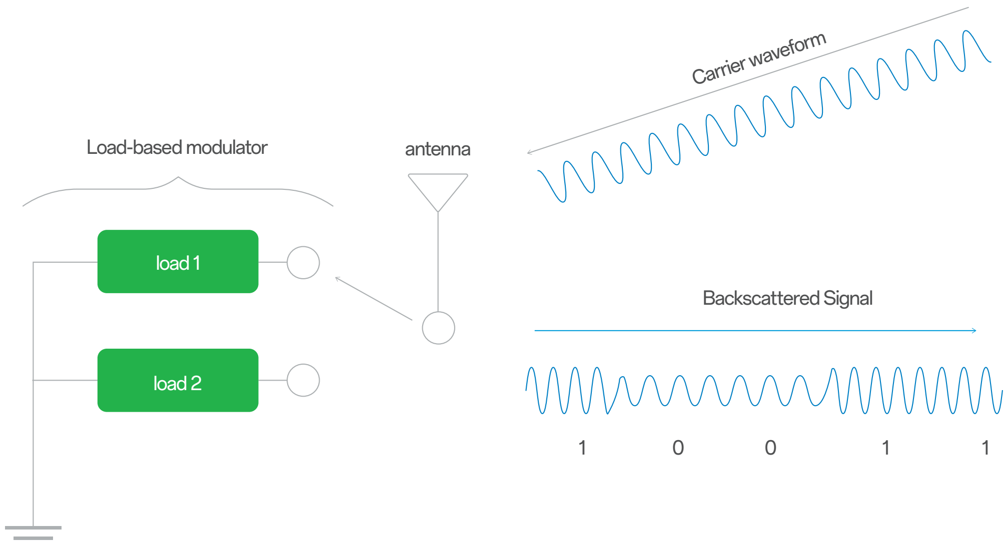

Figure 3.2-4 ASK modulation

Similarly, the terminal can also change the response frequency of the circuit by adjusting the capacitance of the circuit to implement FSK modulation. FSK has better BER performance than ASK. It is often used to realize frequency division multi-access.

Therefore, backscatter communication cleverly utilizes impedance modulation to achieve extremely low-complexity signal modulation and transmission. In contrast, backscatter devices do not require complex RF components such as, high-precision crystal oscillators, duplexers, or high-precision filters. They also do not need complex baseband processing. For example, envelope detection of the signal can be used without the need for complex channel estimation and equalization operations. Therefore, backscatter technology enables the realization of ultra-low complexity backscatter devices.

In the recent Ambient IoT study project carried out by 3GPP, different types of devices are discussed [13]. For the devices supporting backscatter transmission, one type of device has no energy storage or power amplifier, and only supports backscattering without being able to amplify the backscatter signal. Another type of device has certain energy storage and power amplifier and can use the energy stored through energy harvesting to drive the power amplifier to amplify the backscatter signal to enhance the coverage [14].

The typical topologies of Backscatter communication (BC) systems can include the following types: MoBC(Monostatic backscatter communication), BiBC(Bistatic backscatter communication), and AmBC, as shown in the figure below [15]:

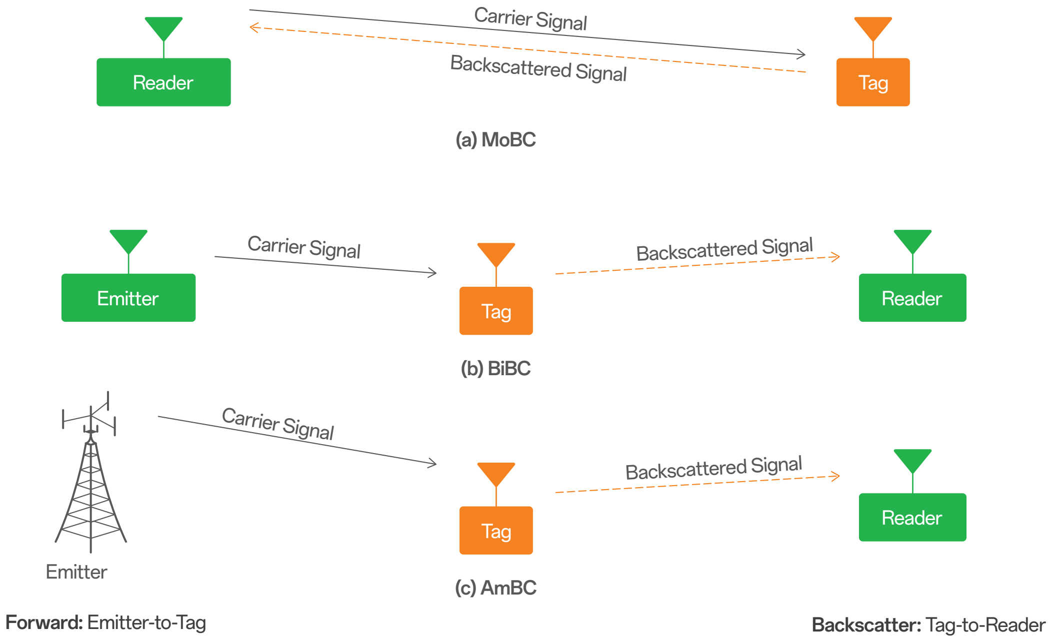

Figure 3.2-5 Typical topologies of Backscatter communication systems

MoBC

The topology includes one reader and one tag (Figure 3.2-5(a)), where the reader provides the carrier for the tag's backscatter and receives the tag's backscattered signal. In this topology, the reader needs to support full duplex with the capability to suppress interference between transmit and receive signals, posing a higher demand on the reader. In order to prevent interference between the transmitted and received signals, the power of the reader's received signal cannot be too weak compared to the power of the transmitted signal. Additionally, the activation power threshold of the tag is relatively high, which results in a shorter coverage distance for MoBC, making it suitable only for short-range applications.

BiBC

The topology includes one reader, one tag, and a dedicated RF carrier transmitter (Figure 3.2-5(b)). The dedicated RF carrier transmitter can be deployed close to the tag, solving the bottleneck of downlink coverage. By separating the transmitter and receiver, the reader does not need to support full duplex. Thus the issue of interference between transmit and receive signals can be bypassed and uplink coverage can be improved. Additionally, optimized deployment of the dedicated RF carrier transmitter can increase the power of the carrier and the efficiency of energy harvesting by the tag, thereby increasing the power of the backscattered signal and improving uplink coverage.

AmBC

Compared to BiBC, this topology utilizes existing RF signal transmitters in the environment, such as cellular base stations, to provide the carrier for the tag, eliminating the need for deploying a dedicated RF signal transmitter. This reduces deployment costs and power overhead. However, because the ambient RF signals are uncontrollable and modulated signals, they can cause direct interference to the reader's reception. The uncontrollability of ambient RF signals limits the performance of AmBC systems, imposing additional design and implementation challenges.

3.2.2 Active signal transmitter

For Ambient IoT devices that transmit signals through backscattering, their power consumption can be as low as a few µW to tens of µW. Energy harvest circuit has certain requirements on the strength of RF signals, generally not less than -20dBm (10µW). This limits the coverage of carrier transmission or wireless energy supply. If Ambient IoT devices have certain energy storage capacity (such as equipped with energy storage components), the RF signal strength can be relaxed to -30dBm. Then, Ambient IoT devices can store energy for use during operation through long time energy harvesting. However, under the circumstances where the power of the energy supply signal is limited, the coverage of energy supply signal from network equipment is still relatively small, generally up to tens of meters. The power of the backscattered signal also depends on the power of the carrier signal. Therefore, due to the influence of downlink coverage, the uplink coverage of Ambient IoT devices that adopt backscatter communication is also very limited. Additionally, as mentioned in the previous section, since uplink signals and downlink carrier signals are typically in the same channel or frequency band in general, there is also a serious issue of uplink-downlink duplex interference.

In recent Ambient IoT study projects in 3GPP and IEEE 802.11 Working Group (WG) [13], different types of Ambient IoT devices were explored. Besides Ambient IoT devices that transmit signals through backscatter, Ambient IoT devices with active signal transmission capabilities can also be supported to improve uplink coverage or solve the duplex interference problem. These Ambient IoT devices generally have large capacitors to store energy from the environment, and their power consumption can support hundreds of µW to several mW. Their transmitters have components such as oscillating circuits, signal amplification circuits, and RF transmit units that are required for traditional transmitters.

- To achieve active signal transmission with extremely low power consumption,the following technical challenges need to be addressed:

1) To achieve extremely low-power signal transmission, an extremely low-power oscillator is required to generate the RF carrier instead of a traditional crystal oscillator. This is because the power consumption of a crystal oscillator is generally several mW [16], which cannot meet the extremely low-power requirement of Ambient IoT devices.

2) The RF carrier generated by an extremely low-power oscillator typically has poor accuracy and requires the development of corresponding frequency synchronization or frequency offset compensation technologies.

3) The output signal power of low-power active transmitters is -20dBm to -10dBm, which significantly increases the coverage of the UL signal compared to the backscatter case (considering the reflection loss, the backscattered signal power is generally -35dBm to -25dBm or lower) [see Section 4.1], meeting the coverage requirements in most scenarios. Such a low output power level is advantageous in terms of controlling the total peak power consumption of Ambient IoT devices. However, it also presents new technical challenges. This is because at the bias voltage levels commonly used today (e.g., 1.5V), a low transmit output power actually reduces the energy efficiency of the entire transmit circuit. Therefore, corresponding techniques to enhance the efficiency of transmission circuits are also required.

Ambient IoT devices with active signal transmission capabilities can independently send signals through the collection and storage of ambient energy, without relying on carrier signals provided by other devices. Their transmitters' amplifiers can increase the signal transmission power, unlike in the case of backscatter transmission, which is limited by the power of the carrier signal. The signal receiving end devices, such as the receivers of network equipment, can achieve a sensitivity level of -100dBm to -110dBm. These advantages can greatly improve the coverage of uplink signals, especially suitable for applications that require large uplink coverage. At the same time, for scenarios that require single-node reception (such as scenarios where smartphones communicate with Ambient IoT devices), it also avoids the problem of full duplex interference in the receiver in case of backscatter.

3.2.3 Ultra-low power receiver

Besides low power transmitter, Ambient IoT devices also need to consider low power consumption and low complexity of receiver to meet the overall power consumption target of Ambient IoT devices. The typical receiver architecture of Ambient IoT devices includes RF envelope detection, heterodyne intermediate frequency (IF) envelope detection, and zero-IF baseband envelope detection architectures, as shown in the following figures:

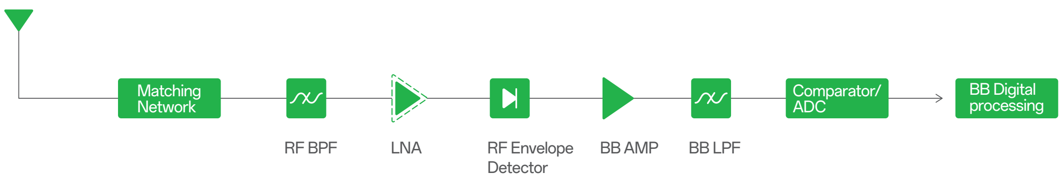

Figure 3.2-6 Architecture with RF envelope detection

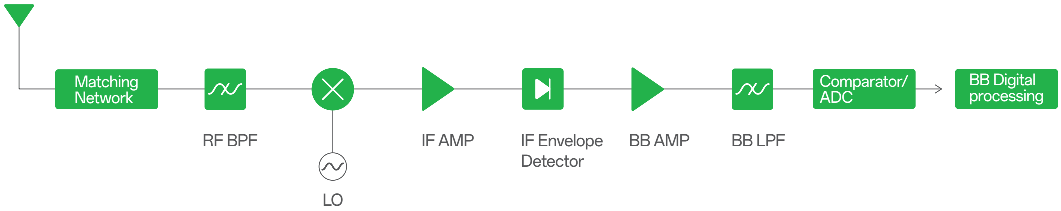

Figure 3.2-7 Heterodyne architecture with IF envelope detection

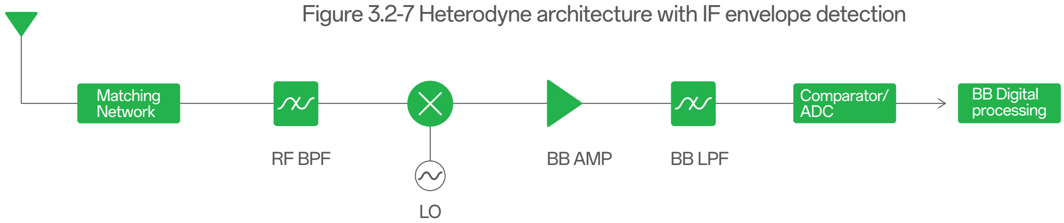

Figure 3.2-8 Zero-IF architecture with baseband envelope detection

The RF envelope detection receiver receives the amplitude-modulated RF signal through a matching network and RF filter. It directly converts the Amplitude modulation (AM) RF signal to a baseband signal through RF envelope detection. This detection method does not require the receiver to have a local oscillator or phase-locked loop (PLL), and can achieve extremely low power consumption with low-precision analog to digital converters (ADCs) and optional amplifiers. Therefore, among the three receiver architectures mentioned above, the RF envelope detection receiver has the lowest power consumption, e.g., a few µW. The receiver needs to use high-Q matching networks and RF filters to suppress adjacent channel interference. However, due to complexity and power consumption, RF analog filters with weak filtering capabilities based on matching networks and filters can not receive the target signal only and reject wide interference signals, resulting in a wide noise bandwidth and poor receiver sensitivity of around -40dBm. The RF envelope detection receiver has the highest noise figure among the three receiver architectures, generally ranging from 12dB to 22dB.

The heterodyne IF envelope detection receiver first converts the filtered RF signal through a mixer to an IF signal, and then performs envelope detection on the IF signal to convert it to a baseband signal. This detection method requires the receiver to have a local oscillator for mixer operation and a corresponding PLL. The added local oscillator and PLL are the main sources of power consumption. Power consumption can be reduced by reducing the precision and stability requirements of the local oscillator, using a frequency-locked loop (FLL) instead of a PLL, and employing low-precision ADCs. Among the three receiver architectures mentioned above, the heterodyne IF envelope detection receiver has the highest power consumption, generally exceeding 100µW. It is more effective for heterodyne IF envelope detection receiver to use IF filters to suppress adjacent channel interference, compared to matching networks and RF filters. It also has RF and IF amplifiers that can improve receiver sensitivity. The sensitivity of the receiver architecture can achieve a sensitivity of -90dBm to -80dBm. The heterodyne IF envelope detection receiver has the lowest noise figure among the three receiver architectures, generally ranging from 9dB to 15dB.

The zero-IF baseband envelope detection receiver converts the filtered RF signal directly to a baseband signal through mixing. This detection method also requires the receiver to have a local oscillator and PLL. The methods to reduce power consumption are similar to those of the heterodyne IF envelope detection receiver. Among the three receiver architectures mentioned above, the power consumption of the zero-IF baseband envelope detection receiver is slightly lower than that of the heterodyne IF envelope detection receiver. The zero-IF baseband envelope detection receiver uses high-Q matching networks, RF filters, and baseband filters to suppress adjacent channel interference. Its receiver sensitivity is slightly lower than that of the heterodyne IF envelope detection receiver. The noise figure of the zero-IF baseband envelope detection receiver is slightly higher than that of the heterodyne IF envelope detection receiver, generally ranging from 10dB to 16dB.

3.3 Low-power computing

The main characteristics of Ambient IoT communication is to realize low-power communication by modulating the incoming carrier waves. At the same time, it can also drive digital logic circuits through RF power harvesting to achieve signal encoding, encryption or calculation.

As mentioned in section 3.1, the conversion efficiency of RF energy is often less than 10%, which means that the power required to drive the digital logic circuits cannot be too high. Figure 3.3-1 shows the number of computing times that 1 microjoule of energy can support. Although with the improvements of the material and optimizations of designs, executions per microjoule can be greatly improved, complex computation using very limited energy remains challenging.

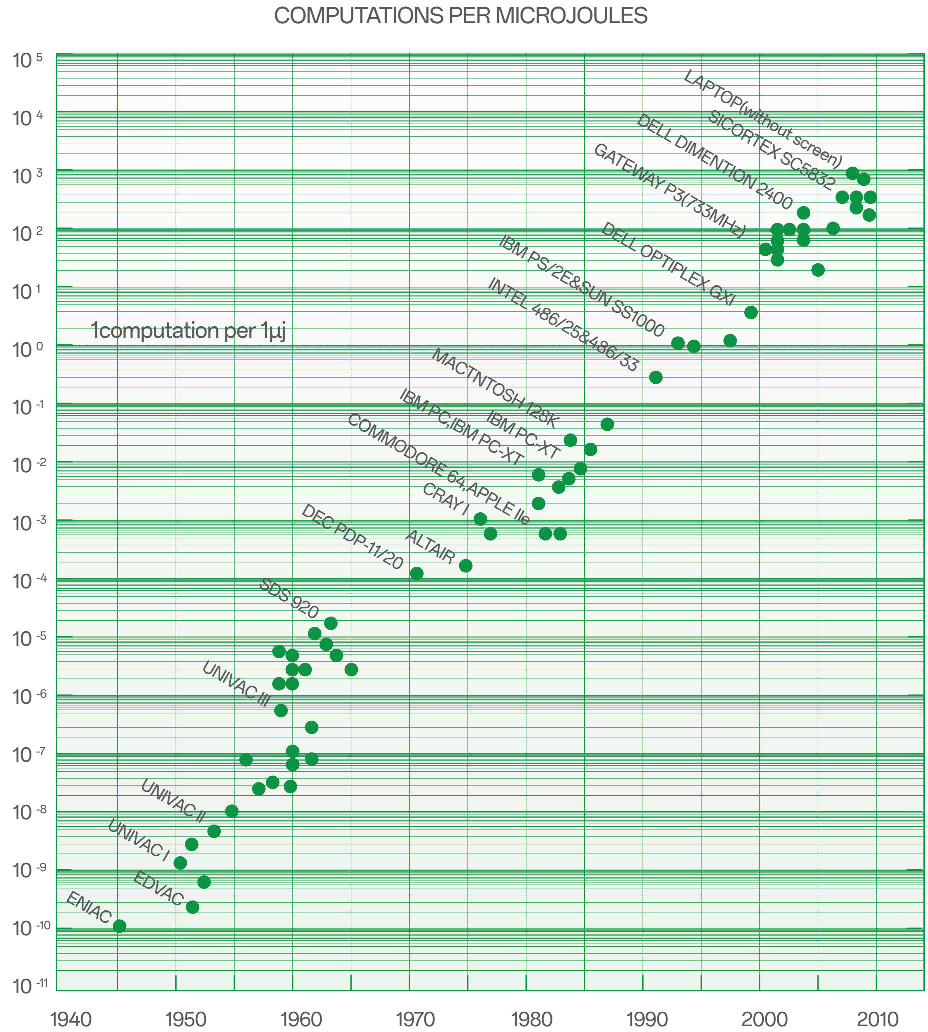

Figure 3.3-1 Computation develops with low power consumption[17]

In order to design the Ambient IoT communication system, low-power computing is usually considered from the following aspects:

Low power-consumption chip

Low power-consumption chips generally include MCUs and sensors. There are minimum input voltage requirements for circuits that drive digital processing chips. As the power consumption is in the order of microwatt for most of the MCUs available in the markets, the harvested energy is usually not sufficient to support complicated communication and computations. Therefore, it is critical to select MCUs and other active components that meet the power budget of the whole system.

Low power security

User privacy and data security shall be considered in many Ambient IoT application scenarios.

On the one hand, it is strongly concerned by customers to protect information such as identification, location etc. For example, in logistics scenarios, it is necessary to write or read item information of Ambient IoT devices; in home scenarios, the location information of personal items is not expected and should not be exposed to non-trusted devices. In order to meet specific requirements for different scenarios, Ambient IoT devices need to support low-power security mechanisms to ensure the confidentiality and reliability of data communication.

On the other hand, due to the low complexity and low power consumption of Ambient IoT devices, whether existing security algorithms (e.g., AES128 encryption and decryption algorithm commonly used in WiFi) can be reused needs to be re-evaluated.

Assuming the following baseband architecture for AES128 [18], using a 65nm processing chip and a data packet length of 128 bits, the power consumption of the AES module and the entire chip are 3.8 µW and 6.5 µW, respectively. The AES128 security encryption algorithm brings microwatt-level power consumption, which makes it possible for Ambient IoT devices.

In addition to AES128, other low-power security algorithms, such as AES 256 and Zu Chongzhi algorithm, are also mainstream choices. In some implementations, random number generators are also introduced.

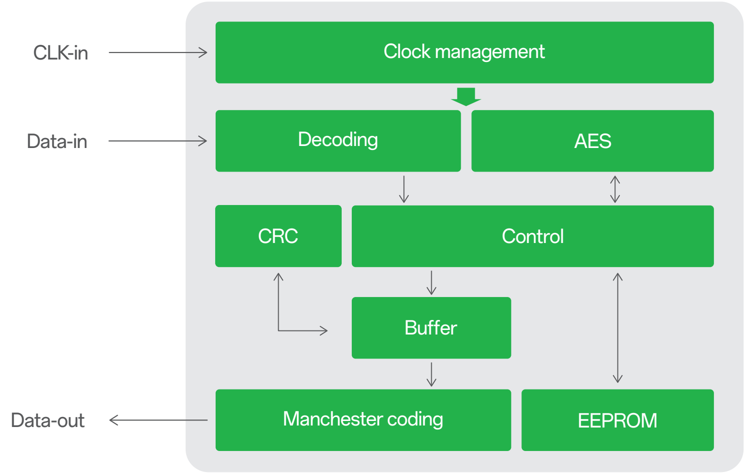

Figure 3.3-2 Example of baseband architecture for evaluating AES128 algorithm [18]

Simple coding and modulation

ASK (including OOK) and FSK can be used as the basic modulation schemes. Simple coding schemes such as non-return to zero (NRZ) coding, Manchester coding, unipolar return to zero coding, differential bi-phase (DBP) coding, miller coding, pulse interval coding (PIE) and other coding methods can be considered. Overall, the use of simple coding and modulation can greatly reduce the power consumption of a Ambient IoT system.

3.4 References

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OVERALL DESIGN OF AMBIENT IOT COMMUNICATION SYSTEM

For different applications, Ambient IoT can use different frequency bands. Different network deployment can be utilized for different communication requirements. Coexistence with existing communication systems should also be considered.

04

4.1 Frequency bands and link budget of Ambient IoT

In the deployment of an Ambient IoT system, its communication frequency band should be appropriately considered first. Selecting different frequency bands will directly affect the design of the overall architecture of the Ambient IoT system. In general, both unlicensed and licensed frequency bands can be used for Ambient IoT.

For operation in unlicensed frequency bands, the spectrum resources can be used freely and flexibly as long as the operation complies with the regulatory requirements. Typical unlicensed frequency bands are globally uniform. Therefore, unlicensed frequency bands can be used to reduce the developing and operating costs and expand the application scenarios of Ambient IoT. According to the latest progress of IEEE 802.11 AMP (Ambient Power enabled-IoT) Study Group (SG), IEEE 802.11 has considered standardizing Ambient IoT in the two unlicensed frequency bands of Sub-1 GHz and 2.4GHz.

For operation in licensed frequency bands, on the one hand, the spectrum resources of existing operators can be fully utilized, and the maximum transmission power on the licensed frequency band is relatively high, which facilitates achieving seamless cellular coverage and long-distance communication. On the other hand, operators can reuse existing widely-deployed cellular network infrastructure and cellular smart terminals to achieve rapid deployment and wide-area coverage for Ambient IoT. According to the 3GPP RAN Rel-19 Ambient IoT SID, Ambient IoT deployed on the licensed FDD (Frequency Domain Duplex) band will be studied in Rel-19.

4.1.1 Licensed frequency bands

Corresponding specification requirements need to be followed for licensed frequency bands. The basic requirement is to comply with local law and regulation to ensure legal, compliant, stable and reliable use of spectrum resources. In addition, it is important for a new communication system deployed on the licensed frequency band to protect existing communication services. The impact on the existing communication system needs to be fully considered to avoid interference to other systems when designing the Ambient IoT system.

From the perspective of spectrum deployment there are three modes for Ambient IoT, including in-band deployment, guard-band deployment and standalone deployment. Different deployment modes represent different spectrum location in the licensed frequency band. No matter which deployment mode is adopted for Ambient IoT, it is necessary to meet the basic RF requirements of the licensed frequency band and consider coexistence with the traditional cellular system. For example, if guard-band deployment is adopted for Ambient IoT, since the division of the guard band is to avoid mutual interference between devices deployed in adjacent frequency bands, potential interference to adjacent frequency bands needs to be evaluated. The interference becomes more severe when Ambient IoT downlink (DL) signal is used to provide wireless power to Ambient IoT devices as the DL signal needs to have sufficiently high transmission power. For another example, if in-band deployment is adopted for Ambient IoT, the existing cellular transmission may cause interference to the reception of Ambient IoT devices. Similarly, the Ambient IoT uplink (UL) transmission also potentially causes interference to the legacy system due to the weak filtering capability. In a word, the coexistence between Ambient IoT and the traditional cellular system needs to be further studied. For relevant detailed analysis, please refer to the following section 4.4.

4.1.2 Unlicensed frequency bands

The related frequency regulation should be satisfied when wireless communication equipment works on an unlicensed frequency band. In the USA, the relevant frequency regulation is given in FCC 15.247. In Europe, wireless systems should follow the "ETSI Harmonized Standards". Theoretically, following these harmonized standards is not a legal requirement. However, the introduction of new devices to the European market is significantly much simpler if devices follow these harmonized standards.

Technically, wireless power transfer is mandatory for backscatter transmission. Meanwhile, it is also necessary to collect and transfer the wireless power for energy storage in the case of active transmission. By taking these points into consideration, high transmission powers are required for energizing Ambient IoT devices. However, the maximum transmission power is limited on unlicensed frequency band in most cases based on the regulations in different countries/regions. Therefore, it is important to pay more attention to the regulatory requirements about the maximum transmission power if the Ambient IoT system operates on an unlicensed frequency band, so as to meet these requirements during the design and deploy phase.

- In the following discussion, the frequency regulation in China, the USA and Europe will be introduced, respectively.

Frequency regulation for 900MHz and 2.4GHz in China

In China, the frequency band of 920-925MHz is mainly for RFID system [1]. The radio transmission equipment doesn' t need to acquire a license on this frequency band but it is forbidden to generate large interference to other existing legitimate radio stations. More specifically, the maximum ERP (Equivalent Radiated Power) is 100mW (i.e., 20dBm) within the frequency range of 920-920.5MHz. And the maximum ERP is 2W (i.e., 33dBm) within the frequency range of 920.5-924.5MHz. Furthermore, the maximum ERP is also equal to 100mW (i.e., 20dBm) within the frequency range of 924.5-925MHz. In the meanwhile, the maximum occupied channel bandwidth is restricted to 250kHz. As for frequency hopping spread spectrum systems (FHSS), the maximum dwell time is 2s for each hopping channel.

The frequency band of 2.4GHz refers to 2.4-2.4835GHz in China and it covers Bluetooth, WLAN (Wireless Local Area Network) and other kinds of wireless access systems [2]. The maximum EIRP (Equivalent Isotopically Radiated Power) is 100mW (i.e., 20dBm) when antenna gain is lower than 10dBi, and the maximum EIRP is 500mW (i.e., 27dBm) when antenna gain is equal or larger than 10dBi.

FCC 15.247 in the USA [3][4]

The frequency regulation in FCC 15.247 covers both relevant frequency bands of 900MHz and 2.4GHz (i.e., 902-928MHz and 2400-2483.5MHz). The maximum transmission power is limited to 1W (i.e., 30dBm). Additionally, the maximum allowed antenna gain is 6dBi. This results in an EIRP up to 4W (i.e., 36dBm).

For FH systems,

From 15.247 (a)(1)(i) The maximum allowed 20 dB bandwidth of the hopping channel is 500 kHz

From 15.247 (b)(2) The max output power shall be 1 watt for systems with at least 50 hopping channels; otherwise, 25 Watts.

In addition, if the 20 dB BW of the hopping channel is less than 250 kHz, the system shall use at least 50 hopping frequencies and the average time on a frequency shall not be greater than 0.4 seconds within a 20 second period. Otherwise, the system shall use at least 25 hopping frequencies and the average time on a frequency shall not be greater than 0.4 seconds within a 10 second period.

For digital modulation techniques,

From 15.247 (a)(2) The minimum 6 dB bandwidth shall be at least 500 kHz

From 15.247 (b)(3) The max output power shall be 1 Watt

ETSI Harmonised Standards in Europe [3][4]

There are multiple harmonized standards in Europe for different frequency bands and it is assumed that the transmission has different characteristics on each frequency band.

1) ETSI Harmonised Standards in the 2.4GHz band

ETSI EN 300 328 covers "Wideband transmission systems; Data transmission equipment operating in the 2.4 GHz band; Harmonised Standard for access to radio spectrum". This standard mainly applies to IEEE 802.11 which is referred as wide-band data transmission. Furthermore, it covers frequency hopping spread spectrum systems (FHSS) (e.g., Bluetooth). The frequency range is from 2400 to 2483.5MHz. The maximum transmission power is 100mW EIRP (i.e., 20dBm).

There are also some additional restrictions when transmission power is higher than 10dBm EIRP. For wide-band transmissions, the maximum power spectral density is limited to 10dBm/MHz. FHSS systems have a maximum transmission TX-sequence time of 5ms, followed by a TX-gap time of 5ms. Additionally, FHSS have to follow additional restrictions concerning the hopping frequency separation.

ETSI EN 300 440 covers "Short Range Devices (SRD); Radio equipment to be used in the 1 GHz to 40 GHz frequency range; Harmonised Standard for access to radio spectrum" . This standard targets RFID system in the 2.4GHz band and other communication systems not covered by ETSI EN 300 328. Unspecific communication devices may transmit with a maximum transmission power of 10dBm EIRP without any additional restrictions.

The allowed frequency range for RFID is between 2446 and 2454MHz, which results in a maximum bandwidth of 8MHz. The maximum transmission power is 4W EIRP (i.e., 36dBm). However, 4W EIRP "shall by technical means be restricted to in building use" and has duty cycle restrictions of 15%. These restrictions do not apply for the communication with transmission power of 500mW EIRP (i.e. 27dBm). However, even in this case the frequency regulation mandates an antenna with ±45 degrees horizontal beamwidth in addition to a side-lobe attenuation of equal or more than 15dB. Furthermore, it requires "physical protection (e.g. antenna dome) which dimension limits a power transfer from the RFID antenna to a quarter wave matched dipole at positioned at an extreme close proximity to +15dBm".

ETSI Harmonised Standards in Europe [3][4]

All in all, the regulation of ETSI on the 2.4GHz band has the following requirements for transmission power:

- For EIRP equal or lower than 10dBm(i.e., 10mW), no additional restriction.
- 20dBm EIRP (i.e., 100mW) in case of frequency hopping or wide-band signals
- 27dBm EIRP (i.e., 500mW) with directive antennas, bandwidth of 8MHz only, can be extended to 36dBm EIRP (i.e., 4W) for stationary indoor use (possible to verticals not sensitive to the cost)

2) ETSI Harmonised Standards in the sub-GHz band

For sub-GHz, ETSI uses the ERP (equivalent radiated power) instead of the EIRP (equivalent isotropically radiated power). A transmitter with 1mW ERP (i.e., 0dBm) is identical to a transmitter with 1.64mW EIRP (i.e., 2.15dBm).

ETSI EN 302 208 covers "Radio Frequency Identification Equipment operating in the band 865 MHz to 868 MHz with power levels up to 2 W and in the band 915 MHz to 921 MHz with power levels up to 4 W; Harmonised Standard for access to radio spectrum".

The frequency range between 865 to 867MHz defines four channels, each channel has a bandwidth of 400kHz. The maximum transmission power is 2W ERP (i.e., 35.15dBm EIRP) with antennas having a beamwidth ≤90° . For omni-directional antennas, the maximum power is limited to 500mW ERP (i.e., 29.14dBm EIRP). The maximum transmission time is 4s, followed by a break of at least 100ms. The maximum transmission power of the tags is -20dBm ERP in addition to a maximum bandwidth of 400kHz in one of the four available channels.

The frequency range of 915 to 921 MHz also defines four channels. However, it is currently available in few European countries only. Power levels of up to 4W ERP (i.e., 38.17dBm EIRP) require antennas having a beamwidth ≤90 ° . For omni-directional antennas, the maximum power is limited to 1W ERP (i.e., 32.15dBm EIRP). The maximum transmission time is again 4s, followed by a break of at least 100ms. The maximum transmission power of the tags is -10dBm ERP in addition to a maximum bandwidth of 800kHz in one of the four available channels.

ETSI EN 300 220-2 covers "Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 2: Harmonised Standard for access to radio spectrum for non specific radio equipment" . Relevant frequency band in the scope of this document is from 863 to 870MHz and from 915 to 921 MHz. It should be noted that the frequencies between 915 and 921MHz are available in few European countries only. The maximum transmission power is typically limited to 10mW or 25mW ERP. However, a higher transmission power of 500mW ERP (i.e., 29.14dBm EIRP) is allowed on band O with a bandwidth of 250kHz from 869.4 to 869.65MHz. However, this band is further limited by a duty cycle of ≤10%.

ETSI EN 303 659 covers "Short Range Devices (SRD) in Data Networks; Radio equipment to be used in the frequency ranges 865 MHz to 868 MHz and 915 MHz to 919,4 MHz with power levels ranging up to 500 mW e.r.p.; Harmonised Standard for access to radio spectrum". This will also cover IEEE 802.11ah.

This frequency regulation allows for 500mW ERP (i.e., 29.14dBm EIRP) if the channel bandwidth is ≤ 200kHz. The available four channels are identical to the four channels defined for RFID usage in ETSI EN 302 208. Additional restrictions are a duty cycle of 10% for AP and 2.5% otherwise. Furthermore, also systems with a bandwidth of up to 1MHz are possible, e.g. IEEE 802.11ah. The parameters are mainly identical to the parameters of the 200kHz mode, but the maximum transmission power is limited to 25mW ERP (i.e., 16.13dBm EIRP).

All in all, the regulation of ETSI on the sub-GHz band has the following requirements for transmission power:

- Highly fragmented into many different bands with different parameters (e.g., duty cycle, transmission power, bandwidth)
- 16.13dBm EIRP (i.e., 25mW ERP) for 1MHz wide channels with duty cycle limitations
- 29.14dBm EIRP (i.e., 500mW ERP) for systems with up to 200kHz bandwidth with duty cycle limitations, one channel with up to 250kHz bandwidth
- 35.15dBm EIRP (i.e., 2W ERP) for RFID systems with directive antennas, bandwidth limited to 200kHz for downlink and 400kHz for uplink
- 38.17dBm EIRP (i.e., 4W ERP) for RFID systems with directive antennas in bands that are only available in some EU countries, bandwidth limited to 400kHz for downlink and 800kHz for uplink

4.1.3 Link budget for Ambient IoT

Like conventional communication, the network coverage of the Ambient IoT system is limited by the transmission power of the network equipment, working frequency band, equipment antenna gains and equipment receiver sensitivity. In addition, it is particularly important to note that the coverage of the Ambient IoT system is closely related to the power level of the wireless energy harvesting signal when energy harvesting is performed based on the RF signal.

Specifically, for the forward link (i.e., the downlink from the network node to the Ambient IoT device), considering that the power consumption of driving the low-power circuit is about several microwatts to tens of microwatts, the signal strength of the RF signal received by the Ambient IoT device can preferably be above -20dBm (10 microwatts), which is also the sensitivity of the current typical RFID tag energy harvesting. It is worth noting that this value is much greater than the receiver sensitivity of traditional terminals (e.g. about -100dBm). If the Ambient IoT device has a certain energy storage capacity, for example, it can be equipped with an energy storage capacitor. The signal strength of the RF signal received by the Ambient IoT device can be relaxed to -30dBm or even lower [5][6], and at this time, the terminal can reserve the energy to be used during operation through energy harvesting for a long time. When RF signals of the same power are provided at the transmitting end, the Ambient IoT device with energy storage capability can have a larger coverage.

In actual deployment, the transmission power of the network node is restricted by regional regulations, e.g., a maximum EIRP of 36dBm, i.e. allowed transmission power of 30dBm, plus the antenna gain of 6dBi, is regulated in the ISM (Industrial Scientific Medical) band. This leads to approximately 50dB link budget, resulting in a fairly limited communication distance.

For the backward link, i.e., from the Ambient IoT device to the network node. The signal strength of the backscattered signal from the antenna of the device would be usually 3~5 dB lower than the input signal, a.k.a. wireless power sourcing signal. The communication distance is restricted by the receiver sensitivity of network node. Fortunately, the receiver sensitivity can achieve as low as -100dBm to -110dBm [7] for a typical network node as implemented in 3GPP. It is thus able to increase the link budget for the backward link up to 80dB, yielding a 30dB coverage extension compared to the forward link.

Based on the above analysis, it becomes obvious that the coverage of the Ambient IoT system is primarily limited by the coverage of the wireless power in the forward link, that is, the forward link is a coverage bottleneck.

In a typical radio frequency identification system, where the ISM frequency band is the target operation band, the maximum coverage would be no more than 10 meters. As seen from the typical use cases in chapter 2, a service coverage distance of up to e.g., 100 meters is envisioned in some use cases. For example, it shall cover a whole factory in the smart manufacturing and industrial monitoring scenarios, and the whole logistics station or warehouse needs to be covered in smart logistics and smart warehousing scenarios. Licensed frequency band can be used in these cases, the allowed transmission power can be increased by about 10 dB on the licensed frequency band compared with a similar implementation in ISM band, which results in about 3 times of coverage extension in the forward link (Consider the limited forward link coverage). Therefore, it also confirms that the use of licensed frequency bands is conducive to the construction of Ambient IoT system that meet the requirements of the vertical industry.

The antenna gain of the device also affects the coverage of the Ambient IoT network. It not only affects the coverage of the forward link, but also affects the coverage of the backward link. In some application, there will be relaxed restrictions on the size and cost of Ambient IoT devices. In order to achieve extended coverage, Ambient IoT devices can use high-gain antennas (e.g. 12dBi receiving antenna gain) to increase the distance of uplink / downlink communication.

In some applications, if the terminal can harvest environmental energy other than RF energy or is equipped with the conventional batteries, the downlink coverage of the Ambient IoT device can be greatly expanded, and the downlink coverage distance will no longer be limited by the signal strength threshold of energy harvesting, but rather by the lower sensitivity of downlink receiver of the Ambient IoT device. Based on the current research, the sensitivity of Ambient IoT device downlink receiver can reach -50/-60dBm or even lower [7-11].

- Take the following three Ambient IoT devices as examples to calculate the link budget, as shown in Table 4.1-1:

Type 1	Ambient IoT device's energy harvesting is based on RF signals of network nodes, and has no energy storage capacity, i.e. the device does not have capacitor or other components for energy storage. It requires that the power of received RF signal is not lower than -20dBm, and backscatter communication mode is adopted.
Type 2	Ambient IoT device' s energy harvesting is based on RF signals of network nodes, has energy storage capacity, and requires that the power of received RF signals should be higher than -30dBm. Backscatter transmission mode or low-power active transmission mode is adopted for communication, and when low-power active transmission mode is adopted for communication, the transmission signal power is about -10dBm ~ -20dBm.
Type 3	Ambient IoT device' s energy harvesting is based on other environmental energy (such as light energy, RF signals provided by third-party equipment, etc.), and has energy storage capability. Ambient IoT device's requirement for the power of the received RF signal from the network node depends on the receiver design (i.e., the receiver sensitivity, which may be considered as -45 dBm). Backscatter communication mode or low-power active transmission mode is adopted for communication, and when low-power active transmission mode is adopted for communication, the transmission signal power is about -10dBm ~ -20dBm (LNA can be used);

A preliminary calculation of the link budget is given in Table 4.1-1. Considering the operational frequency band, transmission power, transmission loss, EIRP of network equipment, antenna gain of Ambient IoT device, backscattering coefficient (the ratio of the signal strength of terminal reflection signal and power supply signal), low noise amplification and other factors, and the communication distance of Ambient IoT is preliminarily evaluated as shown in the following table (calculated based on Friis equation):

Table 4.1-1 Estimation of link budget (Based on Friis equation)

	Type1		Type2			Type3				
	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
	Backs catter	Backs catter with higher antenna gain	Backs catter	Backs catter with LNA	Active transm ission	Backs catter with LNA	Active transm ission	Active transmis sion with high EIRP	Active transmis sion with high EIRP	Higher frequency band
System configuration										
Carrier frequency (MHz)	920	920	920	920	920	920	920	920	920	2400
Network node										
EIRP of Network node(dBm)	36	36	36	36	36	36	36	46	46	46
Receiver sensitivity of Network (dBm)	-100	-100	-100	-100	-100	-100	-100	-100	-110	-110
Ambient IoT device										
Antenna Gain (dBi)	2	12	2	2	2	2	2	2	2	2
Sensitivity of energy harvesting based on RF signal (dBm)	-20	-20	-30	-30	-30	-20/-30	-20/-30	-20/-30	-20/-30	-20/-30
Receiver sensitivity of RF signal (dBm)	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45
Backscatter transmission loss (dB)	5	5	5	5	—	5	—	—	—	—
Tx power of active transmission (dBm)	—	—	—	—	<-20	—	<-20	<-20	<-20	<-20
Low Noise Amplifier factor for backscatter communication (dB)	—	—	—	15	—	15	—	—	—	—
Communication distance (No shadow fading loss)	$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{bf}$									
Network => Ambient IoT (m)	≤20.61	≤65.18	≤65.18	≤65.18	≤65.18	≤366.54	≤366.54	≤1159.11	≤1159.11	≤444.32
Ambient IoT => Network (m)	≥183.71	≥580.93	≥58.09	≥326.68	≤326.68	≥326.68	≤326.68	≤326.68	≤1033.06	≤396.00
Communication distance (With shadow fading loss)	$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{bf} - L_{shadowing\ fading\ loss}$									
Shadowing fading loss (dB)	5									
Network => Ambient IoT (m)	≤11.59	≤36.65	≤36.65	≤36.65	≤36.65	≤206.12	≤206.12	≤651.81	≤651.81	≤246.86
Ambient IoT => Network (m)	≥103.31	≥326.68	≥32.67	≥183.71	≤183.71	≥183.71	≤183.71	≤183.71	≤580.93	≤222.69
Shadowing fading loss (dB)	8									
Network => Ambient IoT (m)	≤8.21	≤25.95	≤25.95	≤25.95	≤25.95	≤145.92	≤145.92	≤461.65	≤461.45	≤176.89
Ambient IoT => Network (m)	≥73.13	≥231.27	≥23.13	≥130.05	≤130.05	≥130.05	≥130.05	≤130.05	≤411.27	≤157.65

Friis equation: $P_{RX} = P_{TX} G_{TX} \left(\frac{\lambda}{4\pi d}\right)^2 G_{RX}$

P_{TX} is the power transmitted to the transmitting antenna. G_{TX} is the antenna gain of Tx. G_{RX} is the antenna gain of Rx. $P_{TX}G_{TX}$ is related to transmit antenna. When the transmitting antenna is matched, the power transmitted to the transmitting antenna is converted into radiated power. $\left(\frac{\lambda}{4\pi d}\right)^2$ is related to the transmission loss of radio waves in free space.

Table 4.1-1 is the link budget estimation based on Friis equation, and preliminary calculation is carried out based on different shadowing fading loss. In the actual deployment environment, in addition to the factors listed in the table, there are other factors such as obstructions and penetration loss. In order to obtain the evaluation results closer to the actual deployment, it is necessary to model different fading loss based on the actual channel. The actual communication distance between network nodes and Ambient IoT devices may be shorter than the values in the table. Table 4.1-1 is only used for qualitative analysis.

The following conclusions can be obtained by analyzing Table 4.1-1 (taking the shadow fading loss of 8dB as an example).

(1) In Case1, the Ambient IoT device of Type 1 harvests energy based on the RF signal sent by the network node. The sensitivity of the receiver is -20dBm (the sensitivity of energy harvesting based on RF signal), and the antenna gain is 2dBi. When the working frequency band is 920MHz and the EIRP of downlink signal of the network node is 36dBm, the maximum communication distance from the network node to the Ambient IoT device is 8.21m. The Ambient IoT device communicates with the network node via backscattering. The Ambient IoT device located at the edge of the network coverage area receives an RF signal of-20dBm, which has a loss of about 5dB during backscattering. At this time, the signal strength sent by the Ambient IoT device in backscatter mode is about -25dBm. Considering that the sensitivity of the network node is -100dBm, the communication distance between the Ambient IoT device and the network node can reach 73.13 m.

(2) In Case2, except for the antenna gain of 12dBi, the other assumptions of the Ambient IoT device of Type 1 are the same as those of Case1. The communication distance from network node to the Ambient IoT device is increased from 8.21m to 25.95m, and the communication distance from the Ambient IoT device to the network node is increased from 73.13m to 231.27m, which is about three times. It can be seen that for an Ambient IoT device, using a high-gain antenna can effectively improve the communication distance if allowed. However, for Type1 Ambient IoT devices, the energy harvesting coverage of DL is the main bottleneck affecting the communication distance between network nodes and Ambient IoT devices.

(3) In Case 3, the Ambient IoT device of Type 2 adopts an energy storage unit, which can reduce the requirement of RF signal strength for energy harvesting from -20 dBm to -30 dBm compared with Case 1. Accordingly, the communication distance between network nodes and Ambient IoT devices has increased from 8.21m to 25.95m, which is about three times. It can be seen that when the energy storage unit is adopted and the threshold of signal strength required for RF energy harvesting of Ambient IoT device is lowered, the communication distance between network nodes and Ambient IoT devices can be effectively increased. In case3, the Ambient IoT device of Type 2 adopts backscatter communication mode. Considering the backscatter loss of about 5dB, the signal strength sent from Ambient IoT device is about -35dBm. At this time, the communication distance between the corresponding Ambient IoT device and the network node is reduced from 73.13m to 23.13m.

(4) In case 4, the Ambient IoT device of Type 2 adopts LNA on the basis of case 3. By using LNA with 10dBi gain, under the condition that the communication distance from the network node to the Ambient IoT device remains unchanged, it can effectively increase the backscatter communication distance from 23.13m to 130.05m compared with case3. It can also increase the coverage range from the Ambient IoT device to the receiving network node when different network nodes send and receive.

(5) In Case 5, the Ambient IoT device of Type 2 adopts active transmission mode for communication, and has the same communication distance from the network node to the Ambient IoT device as case 4. Because active transmission mode is adopted for communication, even the Ambient IoT device located at the coverage edge can still accumulate enough energy over a period of time, and use active transmission mode to send signals with signal strength of -10dBm ~ -20dBm. Taking the active transmission signal strength of -20dBm as an example, the communication distance between Ambient IoT devices and network nodes is about 130.05 m.

(6) In Case 6, the Ambient IoT device of Type 3 does not directly harvest energy based on the RF signal of network nodes, it can harvest energy based on light energy and RF signals provided by other equipment to obtain energy for communication. The communication distance from the network node to the Ambient IoT device is mainly limited by the receiver sensitivity for RF signal of the Ambient IoT device. Taking -45dBm as an example, the maximum communication distance from the network node to the Ambient IoT device is about 145.92 m. When the Ambient IoT device uses backscatter mode to communicate, if the energy of the energy harvesting signal is -30dBm, the backscatter loss is considered to be 5dBm, and a 15dBm backscatter amplifier is used, the transmission power of the backscatter signal is about -20dBm, and the communication distance from the Ambient IoT device to the network node can be about 130.05m.

(7) In Case 7, the Ambient IoT device of Type 3 does not directly harvest energy based on the RF signal of network nodes, it can harvest energy based on light energy and RF signals provided by other equipment to obtain energy for communication. The communication distance from the network node to the Ambient IoT device is mainly limited by the receiver sensitivity for RF signal of the Ambient IoT device, taking -45dBm as an example. At this time, the maximum communication distance from the network node to the Ambient IoT device is about 145.92m. If the Ambient IoT device communicates in an active transmission mode, it can support a communication distance of about 130.05 m.

(8) In Case 8, the same Ambient IoT device assumptions are considered as in Case 7. When the EIRP of RF signal transmitted by network node is increased from 36dBm to 46dBm, the communication distance between the network node and the Ambient IoT device can be effectively increased from 145.92 m to 461.45 m compared with Case 7. However, limited by the receiver sensitivity of the network node and the signal transmission power of the Ambient IoT device, the communication distance from the Ambient IoT device to the network node does not change.

(9) In Case 9, on the basis of the assumption of Case 8, when the receiver sensitivity of the network device is increased from -100dBm to -110dBm, the communication distance from the Ambient IoT device to the network node can be increased from 130.05m to 411.27m compared with Case 8 while keeping the communication distance from the network node to the Ambient IoT device unchanged.

(10) In Case 10, on the basis of Case 9, a higher frequency band is used for communication, for example, from 920 MHz to 2.4 GHz, and it can be seen that the effective communication distance is significantly reduced.

4.2 Topology of Ambient IoT

According to different application scenarios and corresponding system requirements, it can support different Ambient IoT network topologies. According to whether there is a relay node or an assistant node for the data and control link between the Ambient IoT device and the reading node, the network topology of Ambient IoT can be classified into three types: direct network topology, relay network topology and hybrid network topology.

4.2.1 Direct network topology

In the direct network topology, the reader directly communicates with the Ambient IoT device for the transmission/reception of data. Based on different deployment scenarios, direct network topologies can be divided into two types: cellular direct topology and Local Area Network (LAN) direct topology.

4.2.1.1 Cellular direct topology

Cellular-based Ambient IoT systems can support large-scale deployment and centralized control of Ambient IoT devices, aiming to solve the problems of short communication distances, high deployment costs, and low system efficiency of traditional point-to-point and point-to-multipoint IoT technologies (such as RFID). Thanks to the advantages of the cellular network in coverage distance, access capability and resource utilization, the cellular-based Ambient IoT system can manage the Ambient IoT devices in the network in a large range and in a centralized manner, which can greatly improve system efficiency and save deployment costs. Therefore, cellular-based Ambient IoT systems are particularly suitable for certain application scenarios.

In the industrial sensor network scenario, the deployment environment of devices is strict, the number of devices is huge, and the deployment and maintenance cost of traditional active devices are high. The Ambient IoT network based on cellular direct connection can remotely and centrally manage the Ambient IoT devices for control and information exchange. In logistics and warehouse scenarios, a large number of goods need to be identified, tracked, and inventoried. Compared with existing QR code or RFID based methods, cellular-based Ambient IoT systems can overcome the inefficiency and low reliability of existing optical identification and short-range identification, greatly simplifying the identification process, saving manpower and equipment investment, and reducing costs. In the smart farming and animal husbandry scenario, livestock carrying Ambient IoT devices can be managed in the farm through the cellular network, including statistics, positioning, tracking, etc.

As shown in Figure 4.2-1, a cellular-based Ambient IoT system can include the following communication modes:

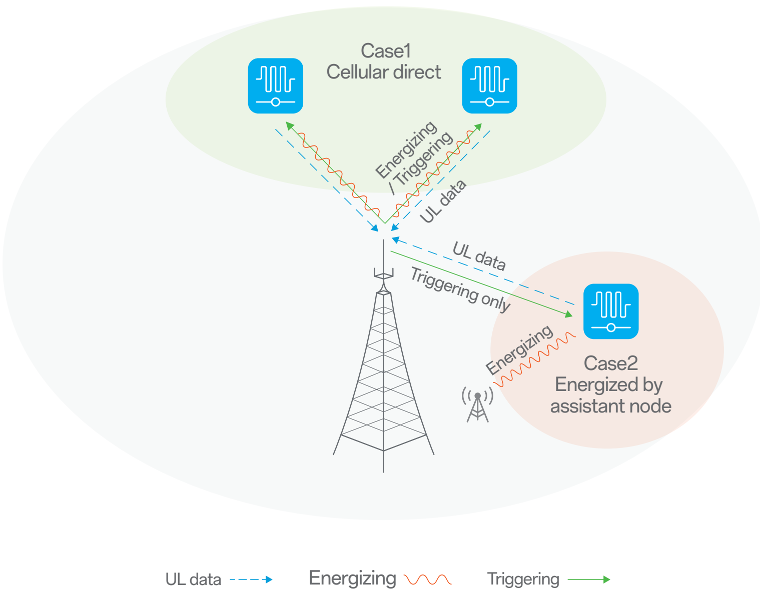

Figure 4.2-1 Cellular direct topology

Case1: Cellular direct

The base station and the Ambient IoT device can communicate directly with each other. The base station provides wireless energy supply signals and trigger signals to the Ambient IoT device. The wireless energy supply signal is used to provide energy to the Ambient IoT device; The trigger signal can carry control information sent to the Ambient IoT device; Ambient IoT devices transmit information to base stations.

It should be pointed out that the Ambient IoT device can send information to the base station by backscattering or active emission. When using the backscatter method, it is necessary to consider how to provide the backscattered carrier to the Ambient IoT device.

- In a typical implementation, the backscattered signal has the same frequency as the incident carrier. At this time, if the incident carrier is provided by the reader, the reader needs to send the backscattered signal of the carrier and receive the Ambient IoT device at the same time, that is, it has full duplex capability, which will significantly increase the implementation complexity of the reader.
- If Ambient IoT devices can support large frequency shifts during backscattering, the implementation complexity of reader can be reduced. However, in order to achieve the frequency shift when backscattering, in one possible implementation, the Ambient IoT device needs to be able to generate a local frequency shift carrier, based on which it is mixed with the incident carrier, and achieve a single sideband backscatter modulation (such as a mirror-suppressing mixture), which will also significantly increase the implementation cost and power consumption of Ambient IoT devices.
- If the Ambient IoT works in the FDD band and the reader is the base station, due to the restriction of regional spectrum regulations, the carrier needs to be sent in the FDD downlink band, but the Ambient IoT device needs to backscatter in the uplink band, and the Ambient IoT device needs to realize the frequency shift from the downlink band to the uplink band during the backscattering. This requirement will greatly increase the difficulty of implementing Ambient IoT devices.

Case2: Energized by assistant node

Ambient IoT devices can not only obtain wireless energy from the base station with which they communicate, but also obtain energy from third-party devices. Through the wireless power supply to obtain energy, the strength of the energy supply signal to the device needs to meet a certain threshold, such as -20dBm (when the device has no energy storage capacity) or -30dBm (when the device has energy storage capacity), which causes limited coverage of the energy supply signal transmitted by the network when the transmit power of signal is restricted, generally in the range of tens of meters to 100 meters. From the perspective of cellular coverage, the coverage of wireless energy supply is much smaller than that of information transmission signals. Therefore, the coverage of wireless energy supply signal is a bottleneck. Wireless power supply through more network nodes can significantly improve coverage, thereby maximizing the cell coverage of the Ambient IoT communication. For this purpose, other nodes in the network can be used for wireless power supply. Potential power supply nodes include smart phones in the network, Relay nodes, CPEs, routers, etc. Where necessary, dedicated power supply nodes can also be deployed. The traditional wireless communication signals sent by these nodes (such as synchronization signals, broadcast signals, data channels, etc.) can provide wireless energy for Ambient IoT devices, or based on reasonable scheduling methods, these energy supply nodes can also send dedicated wireless energy supply signals.

The cellular direct topology with assistant energizing node can not only effectively expand the coverage, but also well solve the above-mentioned full-duplex problem of the base station in the case of backscattering and reduce the complexity when implementing Ambient IoT. With the help of the energy supply signal and carrier signal sent by the third-party device, the base station device is only responsible for the transmission and reception of DL and UL signals between the Ambient IoT devices, without sending the energy supply signal and carrier signal, thus avoiding the full duplex requirement to the base station. Sending the carrier signal through a third party at UL also avoids the problem of local carrier generation for significantly frequency shifting with mirror-suppressing mixture.

4.2.1.2 LAN direct topology

An Ambient IoT based on a direct LAN connection topology enables direct communication between an Ambient IoT device and other types of devices, such as smartphones, WiFi routers, CPEs, or other IoT devices. In the topology of LAN direct connection, direct communication does not depend on the cellular network. This deployment mode also has a wide range of application scenarios, especially for low-cost short-range communication requirements. For example, in the smart home scenario, the direct communication between the intelligent device and the Ambient IoT device can achieve functions such as finding objects, family asset management, environmental monitoring, and intelligent control. In smart wearable scenarios, information reading or intelligent control of Ambient IoT wearable device can be achieved.

An Ambient IoT system based on a LAN direct connection topology can include the following communication modes:

Case 1: LAN direct

The Ambient IoT devices communicate directly with smart devices. The smart device sends the energy supply signal and trigger signal to the Ambient IoT device. Ambient IoT device directly transmit information to smart devices to achieve direct communication. Smart devices can be mobile phones, routers, or controller nodes (such as CPE). The topology maps to Case1-1 and Case1-2 in Figure 4.2-2.

Case 2: Energized by assistant node

In order to realize the direct connection between the Ambient IoT device and the smart device, the wireless energy supply signal to the Ambient IoT device can not come directly from the smart device, but from the third-party device. As shown in Case2 in the figure, the wireless energy supply signal required for the direct connection between the Ambient IoT device and the mobile phone comes from the control node (router or CPE in the figure). After collecting the energy sent by the third-party device, the Ambient IoT device receives the trigger signal sent by the smart device and transmits the information to the smart device.

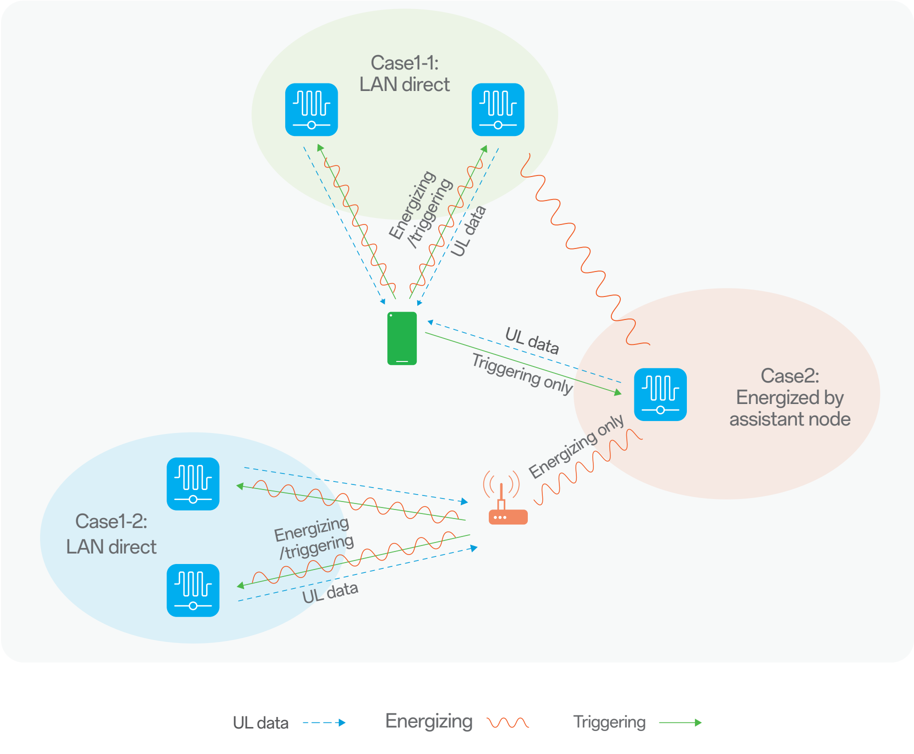

Figure 4.2-2 LAN direct topology

It should be pointed out that for the backscatter type of Ambient IoT device, there is also a full-duplex problem similar to that in the aforementioned cellular direct connection topology, which can also be solved by means of third-party node power supply.

4.2.2 Relay network topology

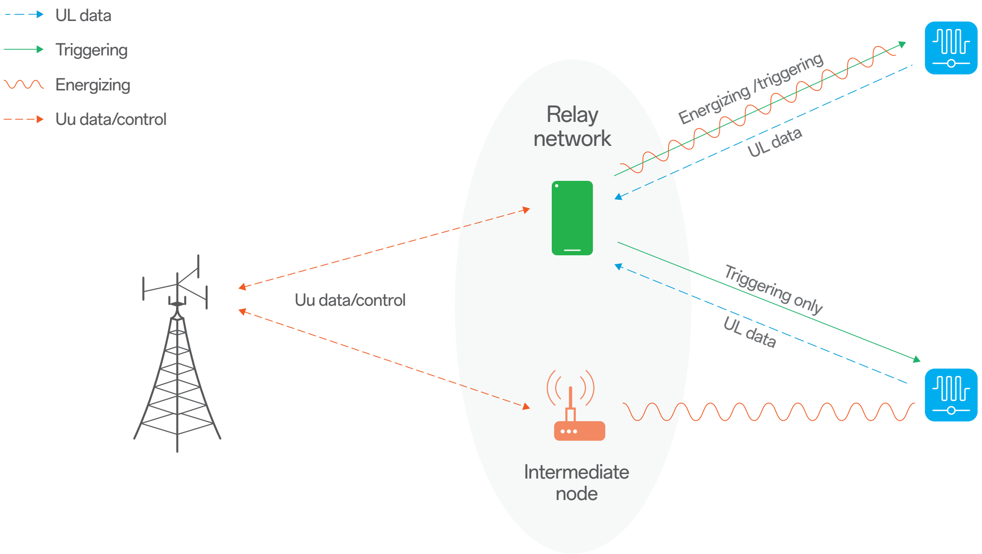

Figure 4.2-3, Relay network topology

In the relay network topology, there is an intermediate node between the reading node and the Ambient IoT device. The intermediate node can be a network relay device or an intelligent device.

- The relay network topology has significant advantages in some application scenarios:

Greatly expand the coverage distance

Due to the complexity and power consumption limitations of Ambient IoT devices, the coverage of the above-mentioned direct connection topology is limited. Intermediate nodes (relay network nodes or smartphones) can be supported to work well under existing cellular network coverage. Therefore, the use of relay network topology can greatly expand the coverage distance and realize the support of Ambient IoT in the existing network topology.

Enable reusing of existing network deployments

With the help of intermediate nodes, the Ambient IoT device can work in the existing network deployment architecture, and the existing network equipment can support the Ambient IoT through software upgrade, so as to reuse the existing network infrastructure as much as possible, and the intermediate node has the advantages of low complexity and easy deployment. Therefore, this method greatly reduces the network deployment cost.

Provide better wireless power

Although the Ambient IoT device can collect a variety of environmental energy, such as light, heat, kinetic energy, etc., in more scenarios, radio frequency energy is still the most important, most reliable, and controllable source of environmental energy. For example, in the aforementioned smart home scenario, the most convenient source of environmental energy for the Ambient IoT device affixed to household items is still radio waves; In logistics and warehouse scenarios, radio waves are still the most likely source of environmental energy, due to the size of the tag and the working environment.

However, the coverage of wireless power supply is relatively limited as analyzed in section 4.1, if only relying on the cell base station directly connected to the Ambient IoT device to achieve wireless power supply. In actual deployment, high base station deployment density is required, which will significantly increase the network deployment cost. Relying on flexible deployment of intermediate nodes to achieve wireless energy supply can greatly reduce the cost of wireless energy supply and achieve better wireless energy coverage.

Support complex and extreme application scenarios

In the actual deployment scenario, there may be serious problems of blocking attenuation, multi-path interference and multi-cell interference. As shown in Figure 4.2-4, in the warehouse scenario, multiple layers of goods may block each other, resulting in severe attenuation of the wireless energy supply signal that can be received by the Ambient IoT devices on some goods, while the signals emitted by the Ambient IoT tags of some goods are also seriously blocked. With the help of intermediate nodes, the problems of energy supply blocking and signal attenuation can be solved flexibly.

Figure 4.2-4 Relay network topology in warehouse scenario

In the cold chain logistics scenario, real-time monitoring of the temperature and other information of fresh goods transported on the road is required. With the help of intermediate nodes deployed on the logistics truck, even in the process of high-speed transportation, the Ambient IoT device attached to the fresh transportation box can still report real-time monitoring information of fresh goods to the network.

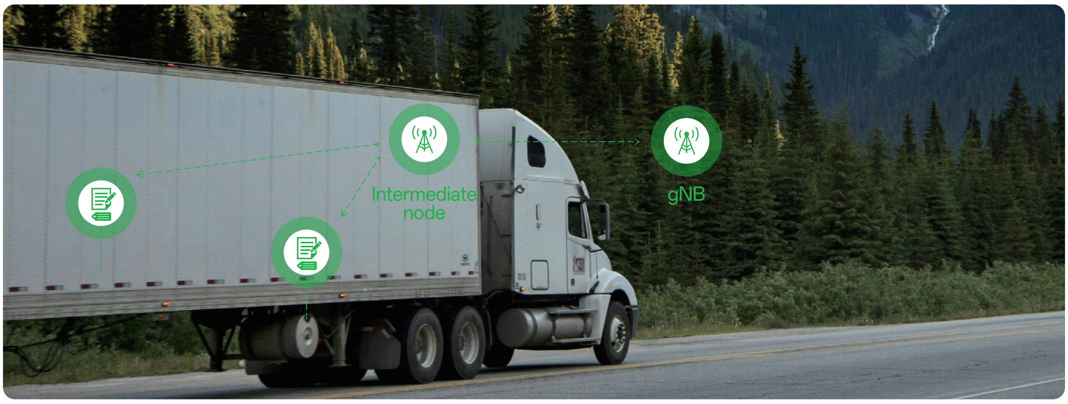

Figure 4.2-5 Relay network topology in cold chain logistics scenario

4.2.3 hybrid network topology

In the actual deployment of Ambient IoT systems, based on the requirements of different scenarios, you can consider the flexible coexistence or combination of the direct network topology and relay network topology to build a hybrid network topology, so as to match more potential application scenarios. The system block diagram of the environment of the hybrid network topology is shown below. Multiple communication modes can be used, as shown in Figure 4.2-6:

Case1: Energized/ triggered by intermediate node

In this topology, the DL trigger signal is provided by an intermediate node, wireless energy supply for wireless energy acquisition/backscatter communication can also be provided by this intermediate node, and the UL signal sent by the Ambient IoT device is received by the base station. Among them, the power supply of intermediate nodes and the operation of sending the DL trigger signal can be controlled by the base station through air interface.

With the help of intermediate nodes to send the DL trigger signal and wireless power supply/backscatter carrier, the topology can effectively expand the coverage of DL communication and wireless power supply. When backscattering is used, because the intermediate node is closer to the Ambient IoT device, it can also provide stronger incident carrier energy, so the communication distance of UL is also improved. In addition, through the separation of DL wireless power supply and UL reception, this method also avoids the full-duplex problem when using the backscatter transmission mode.

Case2: Energized / triggered by network

The base station provides wireless power supply/backscatter carrier for wireless energy acquisition/backscatter communication and sends the DL trigger signal to the Ambient IoT device, while the UL signal sent by the Ambient IoT device is received by the intermediate node, such as an intelligent terminal. Further, the intermediate node sends air interface data to the base station.

With the help of intermediate nodes to receive the UL signals, the topology can effectively expand the coverage of UL communication. In addition, through the separation of DL wireless power supply and UL reception, this method also avoids the full-duplex problem when using the backscatter transmission mode.

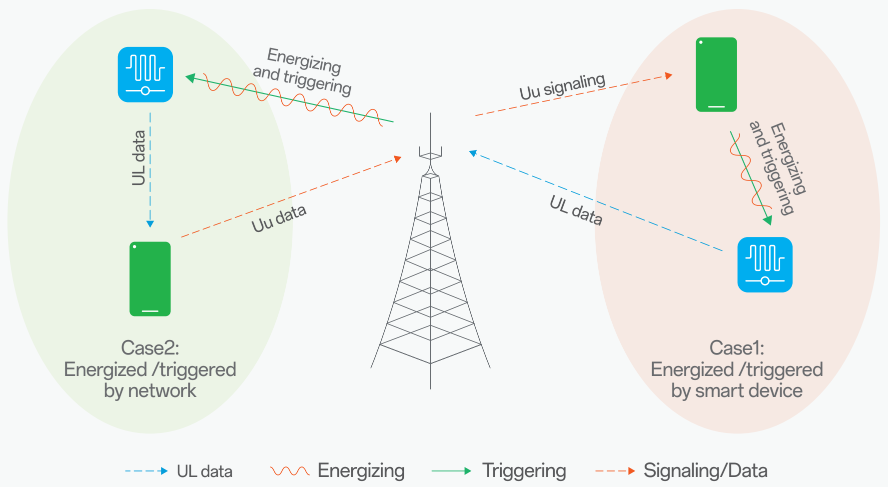

Figure 4.2-6 hybrid network topology

It can be seen from the discussion in this section that different Ambient IoT modes can be considered in different application scenarios based on actual needs. We need to further study the characteristics of various deployment scenarios and communication methods to maximize the application potential of Ambient IoT systems.

4.3 Ambient IoT device type and functionality

Ambient IoT devices can be divided into different device types according to their own characteristics, including energy storage capacity and RF signal generation capacity.

1.Categorization based on whether there is energy storage

Type 1 Ambient IoT devices without long-term energy storage. This kind of devices does not have the ability to store energy for a long time, for example, it cannot continuously store the collected energy for more than several hours. This kind of equipment can drive its own circuit to work by using the environmental energy instantly acquired. As described in Section 3.1, the low energy density of the Ambient IoT device requires very low power consumption of this type of equipment. It should be pointed out that although this kind of equipment does not have the ability to store energy for a long time, it can still use energy storage devices such as tiny capacitors to smooth the instantaneous collected energy to cope with the fluctuation of the collected environmental energy power level in extreme time (such as microseconds or milliseconds).

Type 2 Ambient IoT devices with long-term energy storage capacity. This kind of devices has limited energy storage capacity, and can store the collected energy for a long time, such as several hours or even several days. Ambient IoT devices collect radio wave energy or energy in the environment (such as solar energy, thermal energy, mechanical vibration energy, etc.), and store the collected energy in an energy storage unit (such as capacitor or solid-state energy storage device). After obtaining enough energy, it can drive Ambient IoT devices to send and receive signals, and conduct data processing and other work. Although energy storage devices are used, these devices are also real Ambient IoT devices because they do not need to use traditional batteries and do not need manual maintenance work such as charging.

Type 3 Active Ambient IoT devices. Ambient IoT device uses ultra-low power communication technology for signal transmission. Although with the built-in battery, this type of Ambient IoT devices has extremely low power consumption and complexity, so it can use smaller capacity batteries to achieve smaller volume and save battery cost. The extremely low device power consumption can also greatly prolong the service life of the battery and reduce the maintenance cost of the device.

2.Categorization based on uplink transmission mechanism

Type 1 Backscatter-based Ambient IoT devices. These devices do not have independent signal generators and transmit signals through backscatter. Therefore, when the device performs data transmission, the network is required to provide a carrier, and the device performs backscatter based on the carrier to realize data transmission. Such devices can also use reverse amplifiers to amplify reflected scattered signals to improve coverage

Type 2 Ambient IoT devices based on active transmitter. This kind of Ambient IoT devices has the ability to generate RF signals independently. Therefore, this kind of Ambient IoT devices can send data by using its own active transmitter when sending data, without the need for network to provide carriers

Type 3 Ambient IoT devices with both backscatter and active transmitters. This type of devices can support both backscatter and active transmission. The device can determine which uplink transmission mode to use for data transmission according to different conditions (such as residual power, available ambient energy) or based on the scheduling of network.

3.Categorization based on communication direction

Type 1 Ambient IoT devices with only uplink one-way communication. This device does not need to receive downlink control information from base stations or other control nodes before sending uplink information. When the device obtains enough energy from the surrounding environment, it can send uplink information.

Type 2 Ambient IoT devices with only downlink one-way communication. This device needs built-in receiver to control other devices (such as light switch, start of agricultural facilities, etc.) by receiving downlink control information. In order to ensure the correct reception of one-way control information, the probability of correct transmission can be improved by repeating multiple downlink transmissions.

Type 3 Ambient IoT devices with uplink and downlink two-way communication. This device supports both downlink receiving control information and uplink transmitting information. By receiving downlink control/data information, the device can obtain control information and service data information. In addition, according to the instruction of downlink control information, the device will perform uplink transmission, including uplink feedback, data transmission, etc.

4.Categorization based on shapes and materials

Type 1 Different shapes of Ambient IoT devices. Considering the extensive application scenarios of Ambient IoT, devices can be designed in different shapes to adapt to different scenarios. For example, the device may be in the shape of a square or bar tag, attached to the surface of a box item such as a courier.

Type 2 Different materials of Ambient IoT devices. In order to work normally in different scenarios, device materials usually need to be specially selected or processed. For example, when the device is attached to the metal surface of power device, it is necessary to consider the influence of its own material on the dielectric constant and design the metal-resistant material; Waterproof materials shall be considered when the equipment is used under wet condition; When the device is used to work on soft articles such as documents, it is necessary to consider the use of bending resistant materials; When the device is used as a wearable device, the skin-friendly nature of the material shall also be considered.

5.Categorization based on functionalities

Type 1 Ambient IoT devices providing inventory function. In logistics and warehousing scenarios, the Ambient IoT device can support reading a large number of tags at the same time for cargo inventory. For example, the wireless tag affixed to the goods or containers in the warehouse will record and save the basic information of the goods (such as ID) and the location information in the warehouse. Through the built-in central network node of the warehouse, the goods in the warehouse can be confirmed in time and quickly for warehousing, outbound, storage and other operations, and the quantity of goods can be counted to achieve real-time update.

Type 2 Ambient IoT devices providing environmental information collection function. Ambient IoT devices can be used for environmental monitoring and environmental information collection, e.g., capturing information such as temperature and humidity in the data center or computer room, monitoring the temperature of power devices in the power scene, finding abnormal situations in time, and preventing accidents.

Type 3 Ambient IoT devices providing tracing and positioning function. Ambient IoT devices with extremely small size and waterproof and folding resistance features can be stuck on some easily lost items in the family, such as keys, passports, bank cards and wallets, thus can be used to quickly locate and find lost items when looking for these items.

Type 4 Control-type Ambient IoT devices. By receiving control instructions, it can achieve the function of controlling a certain type of devices. For example, in the smart greenhouse scene of smart agriculture, the Ambient IoT device can not only monitor the humidity of soil, the temperature and humidity in the greenhouse, and the concentration of carbon dioxide, but also receive the control command of the network to control the intelligent irrigation system to increase or decrease the watering amount, control opening or closing of ventilation pipes, or control opening or closing of greenhouse windows, so as to realize the greenhouse environment control.

4.4 Coexistence of the Ambient IoT and other communication systems

4.4.1 Coexistence with cellular communication systems

There are three deployment modes to consider including in-band deployment, guard-band deployment and standalone deployment, when deploying the Ambient IoT in the cellular communications band. In order to avoid mutual interference between systems, it is necessary to study the coexistence of the Ambient IoT and existing cellular communication systems (such as NR, LTE, GSM, etc.).

For the coexistence of the Ambient IoT communication systems and existing cellular communication systems, the most important thing is to analyze the impact of Rx performance, including In Channel Sensitivity (ICS), maximum input power, Adjacent Channel Selectivity (ACS), In-band/out-of-band/narrow-band blocking, and spurious response.

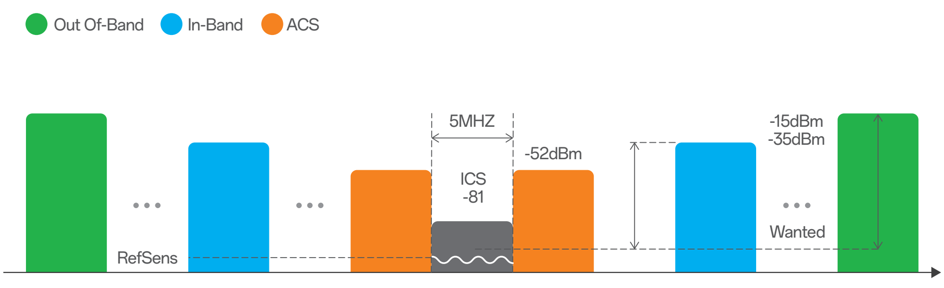

Figure 4.4-1 Basic receiver RF specifications

Firstly, the impact on the receiver performance of conventional cellular systems needs to be considered. The communication signal and the energy transfer signal of the Ambient IoT device may fall into the adjacent band or in-band of the conventional communication system, forming adjacent-band interference or blocking. In particular, for in-band mode, it is necessary to avoid co-channel interference between systems. As described in section 3.1, based on wireless energy acquisition, the input power of the signal received by the Ambient IoT device needs to have a sufficiently high signal strength that is generally greater than -20dbm/-30dbm, which requires the energy supply node to transmit a sufficiently high power energy supply signal. However, there is a limit on the maximum signal strength that can be received by the existing terminal receiver. For example, the maximum input power of the terminal specified in the NR protocol is -15 dBm. Therefore, it is necessary to investigate the impact of in-band deployment on existing terminals and how to avoid the impact.

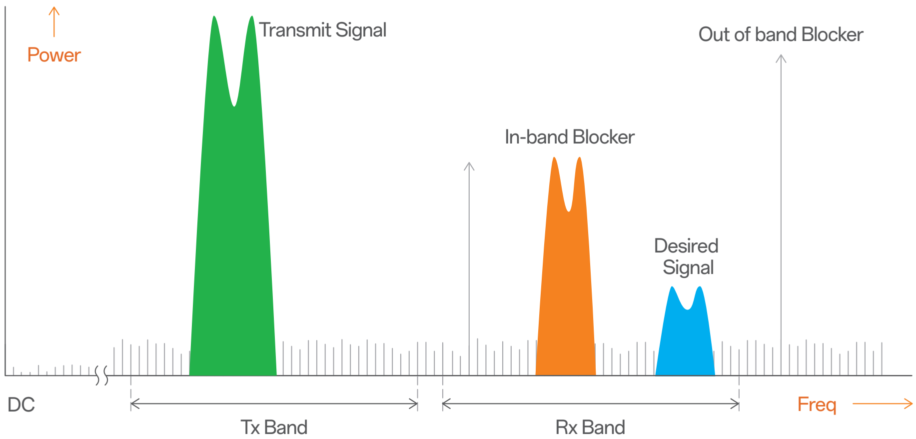

Figure 4.4-2 Receiver blocking

Secondly, it is necessary to consider the impact of UL signals transmitted by the Ambient IoT devices on the performance of receivers in conventional communication systems. The RF link of the Ambient IoT device is extremely simple, and when the Ambient IoT device uses backscatter transmission, the device is difficult to carry out fine filtering of the backscattered signal, resulting in out-of-band leakage of the backscattered signal. For example, if the backscattered signal uses OOK modulation, the spectrum diagram shown in Figure 4.4-3, and it can be seen that sidelobe leakage appears on the spectrum diagram. Thus, it is necessary to assess the impact of these sidelobe leakage on existing cellular communication systems.

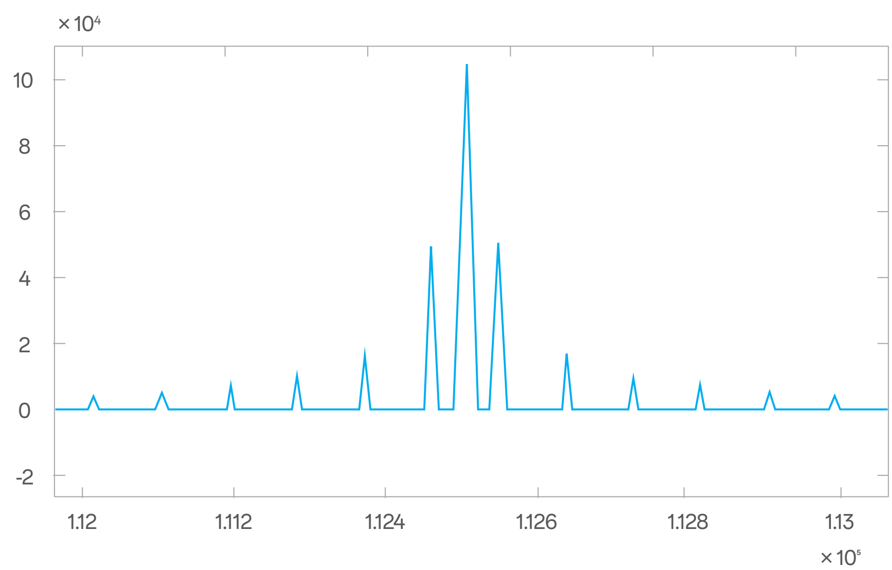

Figure 4.4-3 Spectrum distribution of backscattered signal (OOK modulation)

Finally, the impact of coexistence on receiver performance of Ambient IoT devices needs to be considered. In order to reduce the device complexity and the device power consumption, a class Ambient IoT can use RF envelope detection receivers, which are extremely simple in structure. For example, it does not require an oscillator to down-convert the RF signal, nor does it require a fine signal filter. Thus, the power consumption of this type of receiver can be as low as a few uW. However, even if the Ambient IoT bandwidth is very narrow, such as only a few hundred kHz, the Ambient IoT device will still receive tens of MHz of signals including the Ambient IoT DL signal at the receiver due to the poor overall filtering performance. Therefore, when the Ambient IoT and other cellular systems are deployed in the adjacent frequency, the Ambient IoT device receiver will receive the signals of other cellular systems on both sides together with the Ambient IoT communication signals, which will form strong interference to the reception of the Ambient IoT device DL signal and affect the system performance.

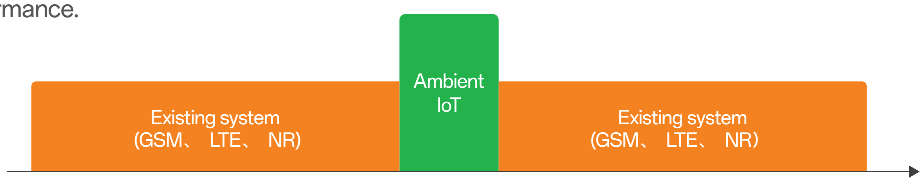

Figure 4.4-4 The DL signal received by an Ambient IoT device contains signals from other communication systems

4.4.2 Coexistence with the communication system operating on an unlicensed frequency band

It is also necessary to consider the coexistence between the Ambient IoT system and the communication system operating on an unlicensed frequency band (such as Bluetooth, WiFi, RFID, etc.) when deploying an Ambient IoT system on an unlicensed frequency band.

Systems operating in all unlicensed frequency bands are required to comply with spectrum usage rules, such as maximum transmit power, frequency hopping, out-of-and leakage requirements, etc., as detailed in Section 4.1. Thus, the Ambient IoT system also needs to comply with the spectrum usage rules of unlicensed frequency bands. More importantly, it is necessary to ensure the fair use of channel resources between systems. Therefore, the devices operating on unlicensed frequency bands are required to do channel listening before sending a signal, that is, to do Listen Before Talk (LBT). However, for the Ambient IoT devices, due to the limited energy they collect, requiring them to perform LBT before transmitting signal will lead to excessive energy consumption, and the limited energy is difficult to support frequent LBT operations. Therefore, how to ensure the good coexistence between the Ambient IoT systems and the existing unlicensed systems, while avoiding the excessive power consumption of the Ambient IoT device to execute LBT is a problem that needs to be solved.

A possible solution is to use channel sharing mechanism. In the Ambient IoT systems, when the device needs to send signals, the network device should assist in occupying the channel and sharing the transmission opportunity with the Ambient IoT device, so that the Ambient IoT device does not need to perform LBT to send date during the time when the network device shares the channel.

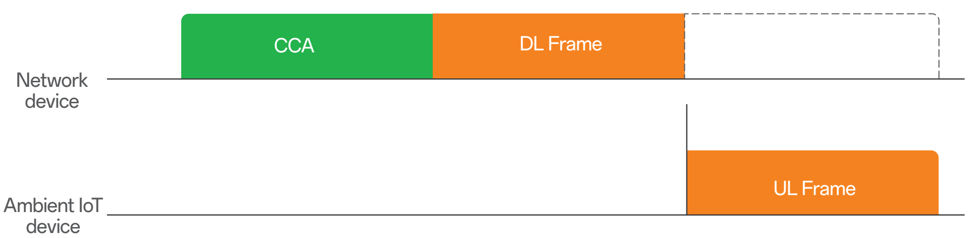

Figure 4.4-5 Network devices share sending time with the Ambient IoT device

4.5 Reference

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KEY TECHNIQUES AND CHALLENGES OF AMBI-ENT IOT

Ambient IoT devices rely on the energy obtained externally. In order to support Ambient IoT, RF radio energy will be a very important source of ambient energy. In Section 5.1, we will analyze the requirements and challenges of wireless power supply for supporting Ambient IoT. Further, in order to adapt to the minimalist hardware structure and ultra-low complexity for the Ambient IoT device, we will analyze the challenges of data transmission of the Ambient IoT device in Section 5.2, including potential modulation scheme, coding, multiple access, resource allocation and synchronization. The dependence on wireless power and the minimalist software and hardware structure of the device also requires lightweight protocol stack and lightweight security mechanism, which will be described in section 5.3 and section 5.4 respectively. Finally, Ambient IoT also imposes new requirements for network architecture. We will discuss the simplified network architecture suitable for Ambient IoT in section 5.5.

05

5.1 The requirements and challenges of wireless power sourcing

As described in Section 3.1, the Ambient IoT device itself does not need to contain a battery. Therefore, before communication, the device needs to harvest ambient power to obtain the energy needed. As explained in Section 3.1, based on different application scenarios, different ambient energy sources (e.g., light, heat, etc.) can be used for energy harvesting. Nonetheless, RF radio wave is favored to be used as a source of ambient energy in many application scenarios due to its controllability and widespread availability in wireless communication networks.

In order to support the Ambient IoT device to communicate in the wireless communication network, it needs to provide wireless power supply to the Ambient IoT device. Compared with the traditional communication system, how to effectively supply energy to the Ambient IoT device in a reasonable way to provide appropriate network coverage is a new challenge for the Ambient IoT system.

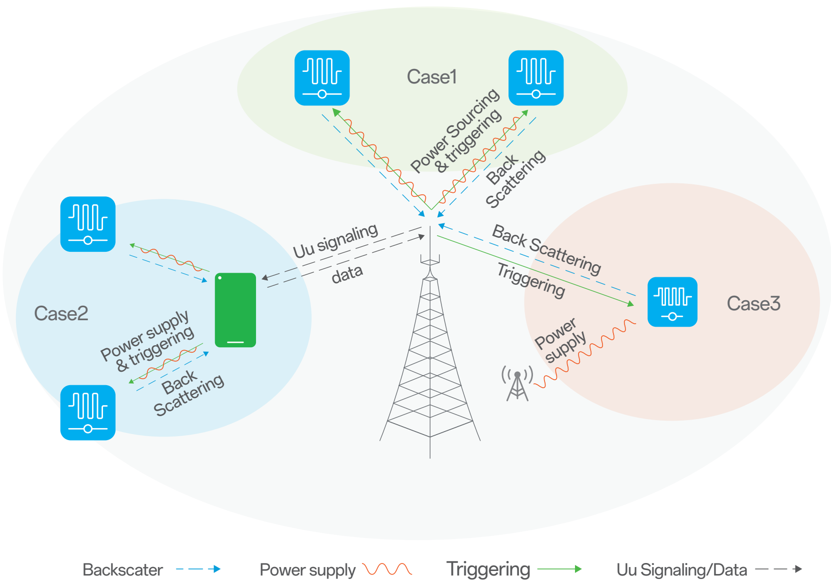

Figure 5.1-1 Various schemes for wireless power supply

Fortunately, there are plenty of network nodes in wireless communication network such as base station equipment, user device equipment, relay equipment, routers, CPE, etc. One of the main functions of all these network nodes is to transmit wireless signals. Therefore, these devices can be used to provide wireless power to Ambient IoT consumption devices.

As shown in Figure 5.1-1, when the Ambient IoT device is deployed in the cellular network, the base station can directly send wireless power supply signal to the device, as shown in case 1 in the Figure. In this case, each time before the base station communicates with the device, it needs to send a wireless power supply signal to charge the device so that it obtains sufficient energy to be activated. In the communication process, the wireless power supply signal also needs to be continuously transmitted to enable the device to obtain the energy required to maintain normal operation. For example, in the process of downlink communication, the device needs to receive the wireless power supply signal to obtain the energy needed to maintain the device for downlink signal reception, signal demodulation and other operations. Since the downlink signal carrying information also carries wireless energy, it can also be used as a wireless power supply signal. Similarly, in the uplink communication process the device sends data to the network equipment, it is also necessary to continuously send the wireless power supply signal to the device. At this time, the wireless power supply signal provides the energy required by the device for data acquisition (such as reading data from the sensor or memory), coding and other operations. In addition, the wireless power supply signal can also be used as the carrier signal for backscatter Ambient IoT devices, so that the Ambient IoT devices can perform backscatter of the wireless power signal, thereby completing the uplink signal transmission.

The wireless power supply signal not only goes through the downlink channel, but also carries the backscattered uplink signal through the uplink channel. Especially for passive devices, when the wireless power supply signal arrives at the device, its signal strength shall not be lower than - 20 /- 30dBm (when the device can reserve the harvested energy). These requirements and limitations make it a challenge to build Ambient IoT networks to provide sufficient coverage. As analyzed in Section 4.1, when the base station directly supplies energy to the device, the communication distance is relatively short, which is usually suitable for building a cell with a cell radius of tens of meters to 100 meters. Such kind of cell is suitable for covering logistics centers, storage stations, industrial plants and other scenarios.

In order to further improve the network coverage and expand the IoT applications to more scenarios, e.g., large industrial plants, agriculture and animal husbandry, it can be considered to deploy dedicated wireless power supply nodes to supply energy to Ambient IoT devices. As shown in case 3 in Figure 5.1-1. The dedicated wireless power supply node is responsible for sending wireless power supply signals when the base station needs to communicate with the device, so as to perform the wireless power supply function of the network. With this kind of deployment, the two functions of wireless power supply and Ambient IoT communication can be decoupled. The distributed wireless power supply nodes in the cellular network provide wireless power supply, which alleviates the challenge of network coverage due to wireless power supply, so as to provide relatively large network coverage. Furthermore, dedicated power supply node is mainly used for wireless power supply, so its complexity and deployment cost will be much lower than that of base station. Therefore, it is a relatively economic way to deploy Ambient IoT network with relatively large coverage.

For application scenarios such as smart wearable or smart home, it generally needs short-range communication. For example, the coverage requirement of smart wearable network is less than 5m and the coverage of smart home is generally about 10 meters. Therefore, as shown in case 2 in Figure 5.1-1, the Ambient IoT network that is centered on smart phones or CPE nodes provides a very attractive short-range personal communication network. The use of nodes such as smart terminals or CPE with transmit power complying with the regulation requirements is also sufficient to provide adequate Ambient IoT communication coverage (refer to Section 4.1).

- From the perspective of wireless power supply signal, at least the following requirements shall be considered.

To provide sufficient wireless power

For the passive device without a battery, when the wireless power supply signal arrives at the device, its signal strength shall not be lower than a certain strength such as -20dBm (when the device has no energy storage unit) or -30dBm (when the device has energy storage unit).

Efficiency of wireless power supply

From the perspective of signal waveform, although any kinds of radio waveform can provide energy for the Ambient IoT consumption device, it can be further investigated whether there are differences in the efficiency for different waveforms, and reasonable waveforms based on that can be designed.

Stability of wireless power supply

When the Ambient IoT device is working, it is necessary to provide stable wireless power supply. Continuous sine waves can provide radio waves with stable power because of their constant amplitude. In the case of wireless power supply using a downlink signal carrying information, the power supply signal is a modulated waveform. Based on the coding of information bits, it is inevitable that the signal amplitude changes. From power supply stability perspective, it is required that the power level of the power supply signal cannot be too low for a long duration. Therefore, in order to ensure the stability of wireless power supply, it requires that the modulated waveform should be carefully considered when selecting coding and modulation scheme.

Compatibility with other systems

When the Ambient IoT system is deployed in the same frequency band with other systems, the impact on other systems needs to be considered. For example, generally the wireless power supply signal needs to be transmitted with high power, so the interference to the adjacent system needs to be considered. When the cellular system is deployed, especially when it coexists with other systems, the wireless signal from other existing systems can be used for wireless power supply thus the source of wireless power supply can be expanded. The base station or smart phone can perform wireless power supply without changing the waveform of the transmitted signal. Therefore, from the perspective of wireless power supply, compatibility with other systems is also worth studying.

Compatibility with backscattering

When the wireless power supply signal is used as the carrier wave for backscattering, it needs to provide enough radio energy. In addition, the impact on the modulation during backscattering should also be considered. For example, when it uses ASK or PSK for backscatter transmission, the sine wave signal of a single frequency is an ideal candidate. However, when the power sourcing signal experiences amplitude or phase modulation such as ASK or PSK modulation, it will produce complex and mixed waveforms, which need to be carefully evaluated for its impact on the demodulation at the receiver. For example, when FSK modulation is used in backscattering, it may be necessary to maintain a stable frequency of the wireless power sourcing signal.

The introduction of the wireless power supply function will have an important impact on the management and allocation of wireless network resources. Similar as legacy resource dimensions, e.g., time domain resources, frequency domain resources and code domain resources in existing wireless networks, wireless power has become a new resource dimension in Ambient IoT system. The network nodes in Ambient IoT system can allocate (transmit) or schedule wireless power according to the communication requirements, so that the battery-less device can still complete the wireless communication function. From the perspective of energy management, the Ambient IoT system changes the power supply from a distributed manner for traditional devices into the centralized manner for Ambient IoT devices. From power consumption point of view, centralized energy supply distributes and uses energy according to demand and it will make the energy use of wireless network more efficient and avoid unnecessary energy waste when there is no communication. In the future, we can further investigate how to maximize the advantages of centralized power supply in Ambient IoT system so as to enable green and low-carbon communication networks.

5.2 Key PHY technologies of Ambient IoT

5.2.1 Modulation and coding of Ambient IoT communication

With the development of wireless communication technology and the improvement of component technology, more complex signal modulation can be used in new communication systems. For example, in addition to supporting low-order modulation methods such as BPSK and QPSK and high-order modulation methods such as 16QAM and 64QAM, ultra-high-order signal modulation technologies such as 256QAM and even 1024QAM are adopted in LTE and NR systems[3]. Similarly, the Forward Error Correction channel coding technology has developed rapidly, and Convolutional code, Turbo code, LDPC code and polar code had been adopted in LTE and NR systems[2]. These modulation and coding techniques play a key role in supporting LTE and NR to realize ultra-wideband and ultra-high speed data transmission.

In the existing technologies of IoT, such as MTC, NB-IoT and RedCap, although the terminal capability is significantly reduced compared with LTE terminals or NR terminals, it basically inherits these traditional modulation or coding methods. For example, MTC/NB-IoT can support modulation methods such as BPSK, QPSK and 16QAM, as well as Turbo and Convolutional codes, while RedCap can also support BPSK, QPSK, 16QAM and 64QAM, LDPC and Polar codes.

However, these modulation and coding methods for ordinary terminals are great challenges for Ambient IoT devices. As described in chapter 3, an Ambient IoT device has a simple RF and baseband structure, for receiving transmitting data in an ultra-low power mode. Therefore, these two aspects will bring strong constraints to the signal modulation and coding methods available to Ambient IoT devices. Specifically, the simple RF and baseband structures make it difficult for Ambient IoT devices to process phase and amplitude modulation and de-modulation. That makes it hard to support QPSK and QAM modulation. Despite the excellent signal encoding and decoding performance, Forward Error Correction channel coding methods such as Turbo, Polar and Convolutional are difficult to support for Ambient IoT devices with ultra-low complexity and low power consumption.

As described in chapter 3, keying modulation technology can be well combined with backscattering technology, so that the terminal realizes ASK, FSK or PSK modulation with extremely simple hardware structure and realizes backscatter data transmission. Using keying modulation technology, the Ambient IoT device only needs to adjust its circuit impedance, capacitance or phase delay on the hardware to implement signal modulation and backscatter transmission. In the other direction, simple signals such as ASK, FSK or PSK can also be received through simple hardware structure. For example, as mentioned in chapter 3, the solution modulation of ASK can be processed through a comparator. That avoids complex baseband signal processing and greatly reduces power consumption.

The channel coding of Ambient IoT devices also needs to match the hardware and software capabilities of Ambient IoT devices. Therefore, more suitable coding methods are based on binary coding, including: non-return to zero (NRZ) coding, Manchester coding, unipolar return to zero coding, differential bi-phase (DBP) coding, miller coding, pulse interval coding (PIE) and other coding methods. These coding methods are simple in baseband processing and generally use high-low electrical level conversion to represent 0 and 1, so they can also be well combined with simple modulation methods such as ASK, FSK or PSK.

On this basis, we can further explore whether more complex signal modulation and coding methods can be further supported under the conditions of minimal hardware and ultra-low power constraints, such as QPSK.

5.2.2 Multiple access methods

For different application scenarios, the Ambient IoT system needs to support varying numbers of terminal devices. Within the coverage area of the Ambient IoT network, multiple Ambient IoT devices may be simultaneously activated and communicating with network devices. Therefore, without introducing a reasonable multiple access method, the backscattered signals from multiple Ambient IoT devices on the same frequency may cause mutual interference. In this case, the network cannot distinguish between different Ambient IoT devices and correctly demodulate the backscattered signals of each device. Therefore, the Ambient IoT system needs to support efficient multiple access methods. Common multiple access methods include Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and Non-Orthogonal Multiple Access (NOMA). This section will discuss multiple access methods suitable for the Ambient IoT system.

TDMA can be considered as a candidate multiple access method for communication in the Ambient IoT system. The Ambient IoT system divides multiple time slots in the time domain. Different Ambient IoT devices can communicate in different time slots based on different time delays. Different time slots isolate the UL signals of different Ambient IoT devices, avoiding mutual interference between UL signals of the devices. TDMA only requires determining a certain time delay and communicating based on this time delay. Therefore, for Ambient IoT devices, TDMA is a simple and feasible multiple access method.

FDMA stands for Frequency Division Multiple Access, which involves dividing several channels with different frequencies in the frequency domain, allowing different users to communicate using different frequency channels. For the Ambient IoT system, it is necessary to explore the feasibility of using the FDMA method. For example, the following aspects need to be considered:

Does the hardware of Ambient IoT devices have the capability to operate on different frequency channels?

The prerequisite for using FDMA for multi-user multiplexing is that terminal devices have the ability to operate on different frequency channels. This seemingly simple requirement for ordinary terminal devices may pose certain challenges for Ambient IoT devices. Constrained by the requirements of hardware complexity and ultra-low power consumption, Ambient IoT devices are not easily equipped with high-precision crystal oscillators and high-precision phase-locked loop. Therefore, generating low-complexity and low-power consumption frequencies and, based on these frequencies, implementing the ability to work on different frequencies will be an important challenge for Ambient IoT devices.

Signal interference levels between Ambient IoT devices on different frequency channels

When Ambient IoT devices send signals to network devices via backscattering, due to the complexity of devices and circuits, backscattered signals generally do not undergo complex shaping filtering before leaving the Ambient IoT devices. Therefore, potential adjacent channel interference may occur for Ambient IoT devices on adjacent channels. How to ensure reliable communication on multiple channels while allowing for the existence of adjacent channel interference is also a worthwhile issue to explore. For example, it may be considered to reasonably reserve frequency guard bands between channels and design receivers reasonably.

Influence on the channel access process of Ambient IoT Devices

Ambient IoT communication is a passive communication method, where Ambient IoT devices need to obtain energy through energy harvesting to drive the circuit into an active state before communicating with the network. Therefore, unlike traditional communication methods where communication processes can be initiated by both network devices and terminal devices, in Ambient IoT communication, communication generally needs to be initiated by network devices. Furthermore, unlike traditional communication processes where terminal devices actively search for networks through cell search processes, Ambient IoT devices remain in a powered-off state until they receive wireless energy provided by the network, thus only becoming activated when network wireless energy is received.

When different Ambient IoT devices support operation on different frequency channels, it becomes necessary to consider how network devices can efficiently trigger the communication process. For example, efficient searching of the channels where Ambient IoT devices dwell and subsequent communication processes, as well as providing appropriate energy supply, are important issues for network devices.

CDMA is a commonly used multiple access method in traditional communication systems, allowing multiple users to communicate using orthogonal multiplexing codes on the same time-frequency resources. Therefore, CDMA communication possesses advantages such as strong anti-interference capability, robustness against fading, good secrecy, and large system capacity. For Ambient IoT communication, adopting CDMA could be beneficial for eliminating interference between users, effectively increasing system capacity, and enhancing communication performance. Particularly, in the case of uplink transmission in Ambient IoT communication, whether using backscatter or active transmission methods, the signal power level is generally weak. Using CDMA, i.e., spread spectrum communication, can also help improve the communication coverage distance.

However, adopting CDMA transmission in Ambient IoT communication may encounter significant technical challenges. For example, CDMA systems have high requirements for synchronization among multiple terminal devices and impose limits on the power difference of received backscattered signals from multiple Ambient IoT devices. Additionally, constrained by the ultra-low complexity, Ambient IoT devices lack high-precision clock generation capability, resulting in weaker synchronization capability. When using backscattering, flexible power control is also difficult to achieve. Therefore, effective implementation of CDMA transmission requires further exploration.

5.2.3 Data transmission and resource management

The traditional cellular mobile communication system supports flexible duplex mode, flexible multiple access mode and data transmission of various types of services. Therefore, data transmission supports flexible and efficient resource management and allocation. For example, the traditional cellular mobile communication system can support resource allocation with variable time, frequency, code and even power domain resource granularity. From the perspective of the signaling for resource allocation, it can support dynamic and semi-static scheduling grant (for example, NR supports configured grant transmission). In addition, the system can flexibly schedule the data transmission of terminals according to the system load, the number of terminals, the UE type and priority of services.

As described in Chapter 2, in the deployment scenario of Ambient IoT, a large number of terminal deployments can be realized due to its advantages of low cost and battery free. The traffic of Ambient IoT is characterized by uplink dominated and small data transmission. For different Ambient IoT scenarios, there are different data transmission requirements and characteristics. For industrial monitoring scenarios, it is mainly used for industrial data reporting and environmental monitoring and the traffic is often periodic. For smart home services, such as home asset management and switch control, the traffic is often one-shot and bursty. For logistics and warehouse scenarios, the network needs to obtain a large amount of information of Ambient IoT devices in a short time duration. In this case, the resource allocation and scheduling need to support a large number of Ambient IoT devices to transmit within a short time duration.

For different scenarios of the Ambient IoT system, the methods of data transmission are also different. Data transmission in the Ambient IoT system can be roughly divided into three types: Device-terminated (DT) DL data transmission, Device-originated-autonomous (DO-A) data transmission initiated by the terminal and Device-originated-device-terminated triggered (DO-DTT) data transmission.

Device-terminated (DT) data transmission

This type of data transmission usually involves a network or other device sending data to an Ambient IoT device, but the Ambient IoT device does not need to send data. For example, in the scenario of smart control of home equipment, instructions can be sent through the mobile phone to control the turning on or off of home appliances. At this time, you only need to send commands to the home equipment through the mobile phone. Generally, it is not necessary for the home equipment to send data. In some scenarios, in order to ensure that the terminal device receives the instruction correctly, the terminal device can send information indicating whether the instruction message is received correctly. In DT type data transmission, since it is mainly downlink data transmission, it is necessary to ensure that the Ambient IoT device can receive the downlink data sent by the network. The downlink data sent by the network can be sent through broadcast, multicast or unicast.

Device-originated-autonomous (DO-A) data transmission

Data is generated on the Ambient IoT device, and data transmission is initiated autonomously by the Ambient IoT device. For example, in the smart home scenario, an Ambient IoT sensor is placed in the kitchen to monitor whether there is a gas leak. When the gas concentration exceeds a threshold, the Ambient IoT sensor actively initiates data transmission, such as initiating an alarm or sending data to the house owner through the network. For another example, in the smart grid scenario, Ambient IoT sensors are used to monitor the temperature, humidity, pressure, vibration and other data of the power grid system, and periodically report the monitoring data to the network, thereby determining whether the entire power grid system is working normally. In DO-A type data transmission, data transmission is triggered by an Ambient IoT device. It can be sent based on event triggers or periodically. In order to ensure that the Ambient IoT device can send data quickly, it needs to support fast access mechanism, or allocate semi-static transmission resources to Ambient IoT devices, so that Ambient IoT devices can obtain corresponding transmission resources when they have data to transmit.

Device-originated – device-terminated triggered (DO-DTT) data transmission

This type of data transmission is triggered by the network signaling to trigger the Ambient IoT device to perform uplink data transmission. For example, in logistics and warehouse scenarios, when goods arrive at the warehouse, new goods need to be registered for goods stocktake so that the system can determine which goods are stored in the warehouse. At this time, the network sends a trigger command, and the Ambient IoT device reports identification information to the network based on the command information, so that the network side can maintain and update the inventory list. In DO-DTT type data transmission, when the network sends trigger signaling, there are usually a large number of Ambient IoT devices that need to transmit uplink data at the same time in a short time. At this time, how to avoid collision, interference among Ambient IoT devices needs to be resolved.

Because the service type, energy supply and terminal characteristics of Ambient IoT are different from those of traditional cellular mobile communication systems, it imposes new challenges to the data transmission and resource management of Ambient IoT.

Challenge 1: Restriction of power supply for Ambient IoT communication

For traditional terminals, data transmission depends on communication requirements and network resource scheduling. The energy supply does not need to be considered in the procedure of data transmission. For the Ambient IoT device, any data transmission of the terminal depends on external power supply. The stability and availability of wireless power supply, energy storage status and energy storage capacity will affect data transmission. Resource allocation and scheduling need to consider the impact of these factors. The wireless power supply shall guarantee the reliable transmission of data. In addition, the resource overhead of wireless power supply on the network side shall be as small as possible to realize on-demand wireless power supply. Therefore, from the perspective of resource management, the resource allocation of Ambient IoT system needs to avoid the interference between users, inter cell interference and the interference of different systems on Ambient IoT, so as to make the Ambient IoT under ideal conditions, ensure the success of data transmission and avoid data retransmission as much as possible. On the other hand, the data transmission of Ambient IoT also needs to rely on the reasonably designed power supply signal and efficient cooperation between the power supply process and the data transmission process.

Challenge 2: Data transmission from a large number of terminals in a very short time

For example, for logistics scenarios, data reading and reporting from thousands or even tens of thousands of Ambient IoT devices need to be completed in seconds. In such scenarios, how to reasonably control the access of a large number of terminals is a problem to be solved. Different terminals should transmit in an orderly manner on different resources, while avoiding the collision of data from different terminals and mutual interference. In addition, in such scenarios, before the Ambient IoT device is triggered by the network, all terminals are unknown to the network. A reasonable system access and communication procedure is needed to enable a large number of Ambient IoT devices to be quickly identified and scheduled for efficient data transmission. For this reason, in the Ambient IoT system, it is necessary to consider multiplexing as many users as possible with the permission of terminal capabilities. Typically, several multiple access modes can be supported. Besides TDMA, FDMA and CDMA can be considered to provide sufficient system capacity for Ambient IoT. As shown in Figure 5.2-1, data transmission for different Ambient IoT devices are effectively allocated to different resource units to avoid inter-user interference. A reasonable access control mechanism needs to be introduced to allow efficient resource management while guaranteeing the requirements of services.

Figure 5.2-1 Resource allocation of Ambient IoT

Challenge 3: Impact of ultra-low cost and complexity of Ambient IoT devices on data transmission

Firstly, the resource utilization capacity of the Ambient IoT device has an impact on data transmission. In traditional cellular systems, flexible resource allocation can meet the requirements of different service type with diverse peak rate, latency and so on. It allows higher resource utilization and spectral efficiency. For Ambient IoT devices with extremely low cost and complexity, the flexibility of resource allocation that they can support will be greatly reduced due to the limitations of transmission bandwidth, communication time, power supply, spectrum shift, time-frequency synchronization, etc. Compromise is required between the flexibility of resource allocation and the capability of Ambient IoT devices. Networks can allocate relatively less-flexible resources for Ambient IoT devices. As shown in Figure 5.2-1, the network configures multiple relatively fixed resource units for Ambient IoT devices in a certain mapping manner. The frequent changing of the mapped resource units should be avoided for an Ambient IoT device to reduce the complexity of resource allocation.

Secondly, the weak synchronization capability of Ambient IoT device also has impacts on data transmission. In the traditional cellular mobile communication system, in order to reduce the interference between multiple users and the interference between uplink and downlink in TDD system, the transmission needs to be under a stringent requirement of synchronization. Traditional terminals, such as smartphones, MTC devices and other IoT devices, can meet the synchronization requirements of cellular systems. For Ambient IoT devices with ultra-low cost and complexity, it is generally not possible to be equipped with an oscillator with high accuracy. A simple oscillator with small size and low power consumption, such as RC oscillators, is usually used to provide the clock. However, the accuracy of RC oscillators is poor, with errors up to 1% or even higher. Whether the clock accuracy with such large error can meet the timing requirements of Ambient IoT and how to adapt to that is a problem that needs further study.

Further, for Ambient IoT devices, they don’t have batteries. The energy needed for its circuit to work comes from wireless power supply. Because of the instability of wireless power supply, even if the Ambient IoT device has a simple oscillator, the oscillator will stop working if wireless power supply is not available. The oscillator cannot work continuously to provide a stable and continuous clock. Regarding the effect of time-frequency synchronization on data transmission, please refer to section 5.2.4.

5.2.4 Time-frequency synchronization

The accuracy of time-frequency synchronization achieved by the terminal equipment has certain influence on the design of time-frequency multiplexing of resources and the performance of data decoding. In the pursuit of high data throughput and transmission rate communication systems (such as cellular communication systems, IEEE 802.11ac systems, etc.), OFDM is usually used. OFDM technology requires strict synchronization between subcarriers and is very sensitive to timing deviation and frequency deviation. For example, in the 5G cellular system, the timing deviation of the user device is required to be preferably within the cyclic prefix (CP) range to avoid inter-symbol interference; The precision of the crystal oscillator is required to be ±0.1ppm to ensure the orthogonality [1] between the subcarriers to avoid intercarrier interference. Correspondingly, the 5G cellular system has also designed a relatively complete and complex synchronization mechanism. During the initial access process, user devices can obtain the initial time-frequency synchronization through the 127 bit Primary Synchronization Signal (PSS) and Secondary Synchronization Signal

(SSS). In the follow-up communication process, the Tracking Reference Signal (TRS) can be used to track and compensate the time-frequency deviation, which can meet the time-frequency synchronization requirements of the system. To achieve the reception of these synchronous signals the terminal device needs to have complex signal processing capabilities such as high sampling rate, IQ demodulation, FFT transformation, and so on, which cannot be applied to the Ambient IoT systems.

For systems that communicate with simpler waveforms, the synchronization requirements can be relaxed. For example, the IEEE 802.11ba system using MC-OOK waveform can achieve a timing deviation of ±250ns or even 0ns [2] in most cases through a synchronous reference signal with a sequence length of 32 bits, which is less than the MC-OOK symbol length (the symbol length is 2us in high data rate scenarios and 4us in low date rate scenarios), which does not have much negative impact on subsequent date communication. Such synchronization mechanism does not require the terminal equipment to carry out complex signal processing, and has important reference significance for the synchronization scheme design of Ambient IoT. Specific parameter design, including the structure of synchronization signal, type of synchronization sequence, sequence length, modulation and coding mode, needs to be adapted according to the actual synchronization needs, while taking into account the delay and complexity of synchronization process. Generally, the longer the synchronization reference signal, the higher the synchronization accuracy, but the corresponding detection delay and complexity will also increase.

Although the synchronization mechanism of IEEE 802.11ba system can recover timing information more accurately, it cannot realize frequency synchronization. The WUR (Wake Up Radio) terminal device uses a low-power wake up Radio device to monitor the WUR data sent by the network and maintain the basic connection, and wakes up the Main Radio (MR) with high time-frequency synchronization accuracy to send and receive data when necessary. Since WUR only involves the reception of DL signal, and DL signal adopts MC-OOK waveform, WUR terminal device can use envelope detector for non-coherent demodulation without requiring high precision frequency synchronization. In some practical applications, even if the center frequency of WUR is not accurately synchronized with the network, WUR can still receive DL signals correctly with some loss of receiver sensitivity. In addition, since WUR acts as an auxiliary receiver, it is possible to share the power supply and even the clock circuit with the main receiver. Therefore, on the one hand, WUR can tolerate a larger power budget to achieve a more accurate clock circuit, and on the other hand, it can also obtain a more accurate clock by sharing the clock circuit of the main receiver. However, frequency offset is a problem that cannot be ignored for Ambient IoT.

Different from the WUR device, in order to strictly control the complexity and power consumption of the Ambient IoT device, the Ambient IoT device is only equipped with a set of RF devices with weak capabilities. It usually contains a simple local oscillator or even no oscillator, and based on such RF devices, it is necessary not only to complete the downstream data reception, but also to achieve the uplink data transmission. For downlink data reception, the above MC-OOK waveform, which is relatively insensitive to frequency bias, can be used. For uplink data transmission, especially for Ambient IoT devices using active transmission mode, large frequency offset may cause uplink transmission to deviate far from the owning channel and interfere with the signals in the adjacent channels, which greatly reduces the reliability of uplink data. Therefore, for the Ambient IoT system, it is necessary to design a reasonable frequency synchronization scheme, so that the Ambient IoT device can achieve sufficient frequency synchronization accuracy under the condition of low power consumption. For example, the terminal device calculates the phase rotation based on repeated reference signals to determine the frequency offset [3]. On this basis, a small amount of frequency deviation can be tolerated by appropriately reserving frequency protection bands in the UL channel, which slightly reduces the frequency spectrum usage efficiency (generally speaking, for licensed frequency bands, spectrum efficiency is an important indicator of system design), but it can reduce the power consumption and device complexity of Ambient IoT devices.

In addition to the above time-frequency synchronization functions, the design of the synchronization signal of the Ambient IoT system can also have other functions, so that the ambient IoT device can obtain some other important information while detecting the synchronization sequence. For example, the synchronization signal of the existing 5G cellular system carries the Physical Cell Identifier (PCI) for cell identification through 1008 combinations of PSS and SSS sequences; The IEEE 802.11-ba system indicates the data transfer rate through two different synchronization sequences. In the process of standardization discussion, whether the Ambient IoT system needs to synchronize signal carrying information and what information it carries needs to consider factors such as network deployment, date channel design, and business requirements.

5.2.5 Positioning technology for the Ambient IoT communication system

At present, the mainstream positioning technology for satellite system and cellular system can achieve high accurate positioning in outdoor scenarios, while indoor positioning has not been effectively solved due to complicated environmental factors such as multipath and occlusion. However, positioning function is indispensable in some typical application scenarios, such as smart parking lot, warehouse and logistics, smart home and so on. This subsection will analyze the following traditional positioning methods one by one, and screen out the potential solutions suitable for the Ambient IoT system.

TDOA (Time Difference of Arrival)

the basic principle is to construct multiple hyperbolic constraint equations through the propagation time difference between multiple known reference nodes and the target node, and then position of the target node could be estimated.

Multi-RTT (Multi-Round Trip Time)

the basic principle is to construct multiple distance constraint equations through the round-trip time difference of signal transmission between multiple reference nodes and targets node, and then position of the target node could be estimated.

Angle-based positioning method (such as AoA/AoD)

the basic principle is to construct triangular equations by referring to the angle information between the reference nodes and the target node, and then the position of the target node could be estimated.

Cell ID-based positioning method (CID)

the basic principle is to select a serving cell according to the signal strength. Considering that the signal strength is greater with closer distance, the position of the selected cell could be considered as the estimated position of the target node.

Phase-based positioning method

the principle is to estimate the propagation distance based on the phase change of signal between reference nodes and the target node, and then the position of the target node could be estimated.

The performance of any positioning method depends on the related measurement accuracy. Both TDOA and Multi-RTT positioning methods need to measure the time of arrival, of which the accuracy is positively correlated with the signal bandwidth and sampling clock rate at Rx side. The larger the signal bandwidth and the higher the sampling rate, the more accurate the corresponding time measurement is. The resolution of angle-based measurement is related to the number of antennas and their arrangement. Theoretically, the higher the number of antennas, the higher the resolution of angle-based measurement. Moreover the angle information measured by two-dimensional antenna array is more abundant than that measured by one-dimensional linear antenna array. However, neither large bandwidth nor high sampling rate can be implemented in Ambient IoT devices. For network equipment, configuring antenna array will also increase deployment costs. In some scenarios, such as using a smart mobile phone to locate Ambient IoT devices, it is difficult to deploy antenna array within the smart mobile phone. In summary, the positioning method based on time measurement is not suitable for Ambient IoT systems, and the application scenarios of angle-based positioning method will be quite limited.

Cell ID-based positioning method is simple and easy to implement. The device is only required to measure the signal strength, such as RSRP or RSSI, of multiple candidate base stations. According to the measurement results, the base station with the best signal quality will be selected and its position will be considered as the estimated position of the device. Although the measurement accuracy of signal strength such as RSRP is highly related with the number of reference signal resources, it could be improved by multiple measurements in the time domain rather than mandating a larger bandwidth for the reference signal. Due to the large coverage of a cellular cell, which could be hundreds or even thousands of meters, large positioning error obvious exists when using cell ID-based positioning method. Fortunately, the low-cost characteristic of the Ambient IoT devices makes it possible to deploy massive devices as positioning reference tags with high density, such as at intervals of 2 meters or even denser for the indoor scenario, thereby significantly improving positioning accuracy.

Figure 5.2-2 shows a positioning method similar as the above-mentioned cell ID-based positioning method. The target device will measure the signal strength of multiple Ambient IoT reference tags, select the reference tag with the highest signal strength and take its position as the estimated position. This positioning method is suitable for the indoor navigation case. Users can determine their own position according to the reference tags around them, and determine the approximate walking direction and route according to the target position and passing reference tags.

The other typical positioning scenario is object search, in which the handheld mobile phones and the network devices could measure the signal strength of the target device and the reference tags respectively, and the position of reference tag whose measurement result is the nearest to that of the target device is the estimated position. To further improve the reliability and accuracy of positioning, the first k nearest reference tags can be selected, and the K-Nearest Neighbor (KNN) algorithm can be used to determine the position of the target device [4]. Figure 5.2-3 shows the Cumulative Distribution Function (CDF) of positioning errors by using the KNN algorithm when the reference tags are deployed at intervals of 4m, 2m and 1m respectively. It shows that the positioning accuracy of 6m could be achieved in ideal conditions.

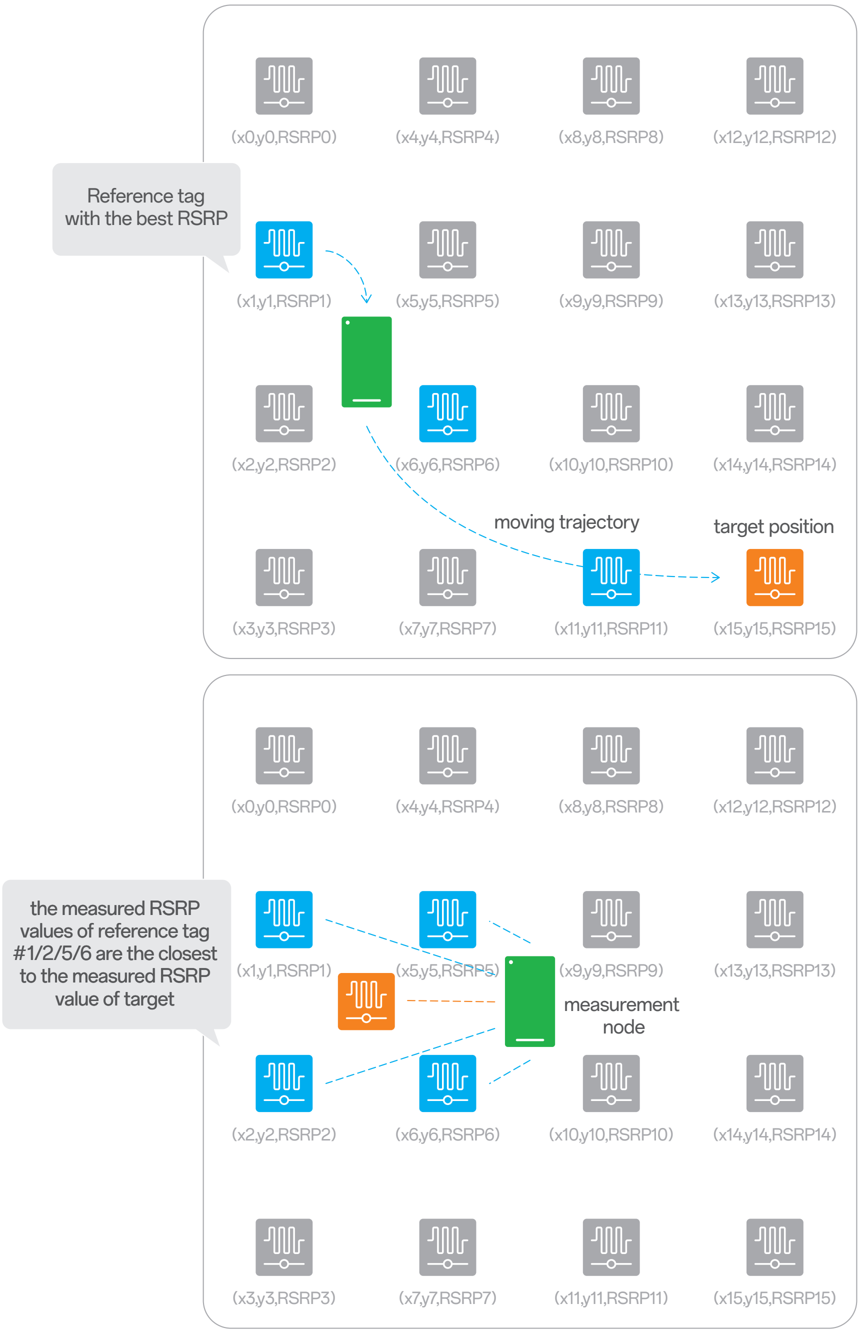

Figure 5.2-2 Signal strength-based positioning method with reference tags

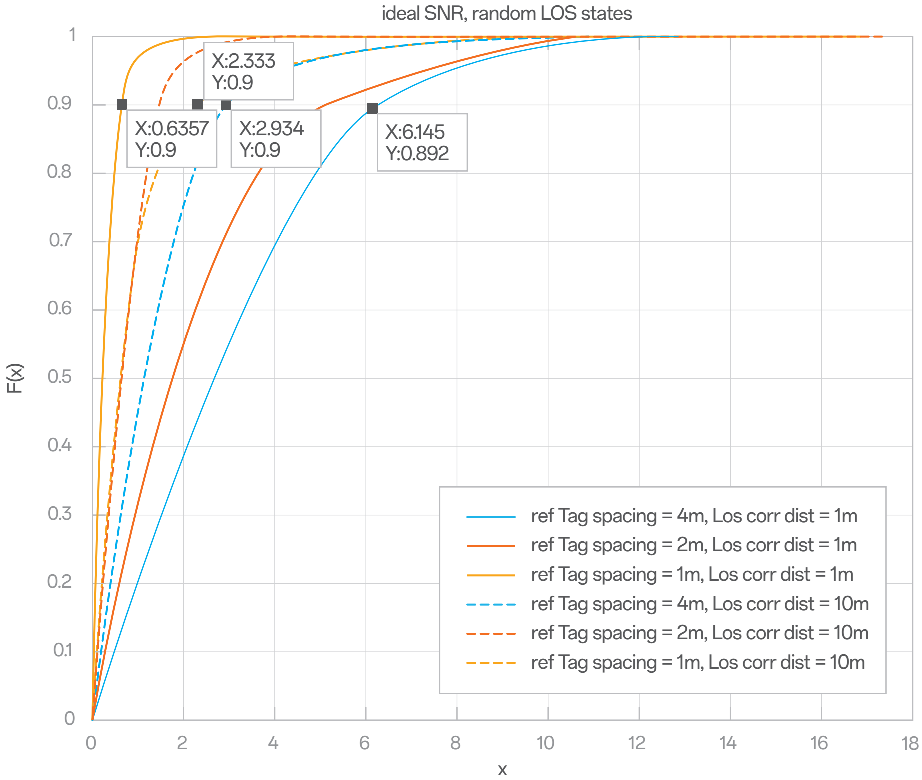

Figure 5.2-3 CDF of positioning errors for signal strength-based positioning method

High accurate positioning can be achieved based on phase information, which is currently widely used in Bluetooth and satellite positioning systems. Similarly, the measurement accuracy of the phase information will also affect the final positioning performance. As shown in the figure 5.2-4, phase measurement is performed by comparing the received signal y with the local signal x to determine the phase difference between them. In theory, the positioning reference signal in this method can be a simple sine wave, which is very suitable for the narrow band characteristics of Ambient IoT systems. A tricky problem for phase-based positioning method is how to solve the influence of random initial phase. The difference between the initial phase θ_{Tx} and θ_{Rx} at the Tx and Rx sides will cause severe deviation in phase difference measurement, so it is necessary to eliminate the influence of random initial phase.

This problem can be avoided if backscatter transmission is adopted by the Ambient IoT device, where the network device sends and stores the signal x , and the Ambient IoT device will not generate its own signal, but backscatter the signal from the network. At this time, the phase difference ϕ of y received by the network device compared with the original signal x is related to the distance d and the frequency f , that is, $\phi = \frac{2\pi * 2d}{c} * f$. Because of the 2π periodicity of phase, only the fractional part can be measured and the whole cycle part cannot be obtained in practice. Then, the range of single-frequency measured distance is half wavelength $\frac{\lambda}{2} = \frac{c}{2f}$. Even with low frequency such as f=1GHz, the range is only 15cm, which is very limited. In order to solve the problem caused by the ambiguity of the whole cycles, the dual-frequency phase difference method [5] can be used by measuring the phase change $\{\phi_1,\phi_2\}$ of two frequencies $\{f_1,f_2\}$. In this case, the phase difference $\Delta\phi=\phi_1-\phi_2$ depends on the distance and the frequency difference $\Delta f=f_1-f_2$, that is, $\Delta\phi = \frac{2\pi * 2d}{c} * \Delta f$. As long as the frequency difference is small enough, the equivalent half-wavelength $\frac{\Delta\lambda}{2} = \frac{c}{2\Delta f}$ could be increased, thereby extending the distance range. For example, the distance range could be up to 150 meters when Δf=1MHz, satisfying the demands of Ambient IoT positioning scenarios with medium and short distance. Figure 5.2-5 indicates the positioning error for phase difference based positioning under the case that the coverage radius of positioning gNB is equal to 70m. According to the simulation result, the accuracy of the phase difference ranging with dual-frequency can reach less than 6 meters. With the distance between target node and multiple reference nodes, it will be easy to estimate the absolute position of the target node by using the classic multi-lateration positioning algorithm, thus realizing indoor navigation and object search functions.

The traditional phase positioning model is as follows:

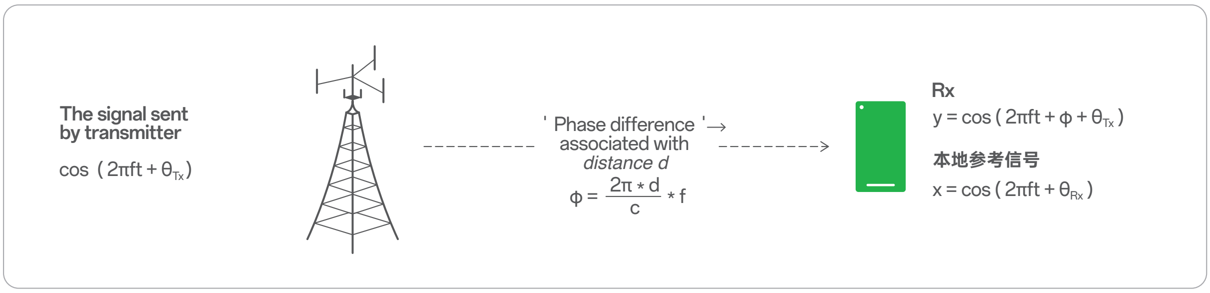

Illustration of traditional phase-based ranging

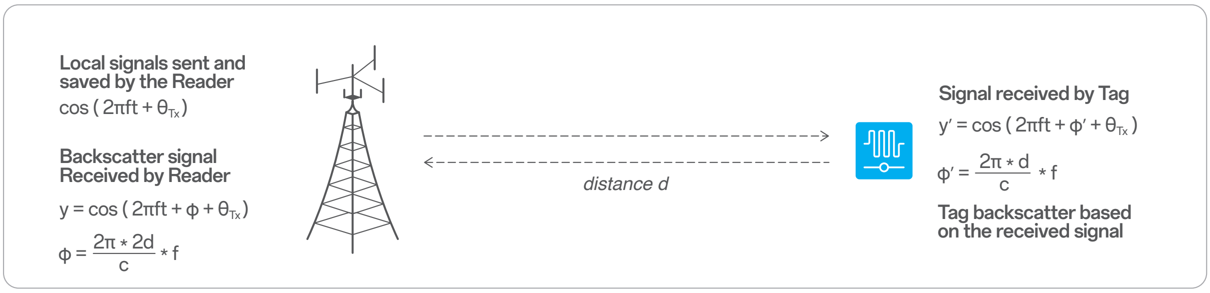

Illustration of phase-based ranging with backscattering

Figure 5.2-4 Illustration of phase positioning model

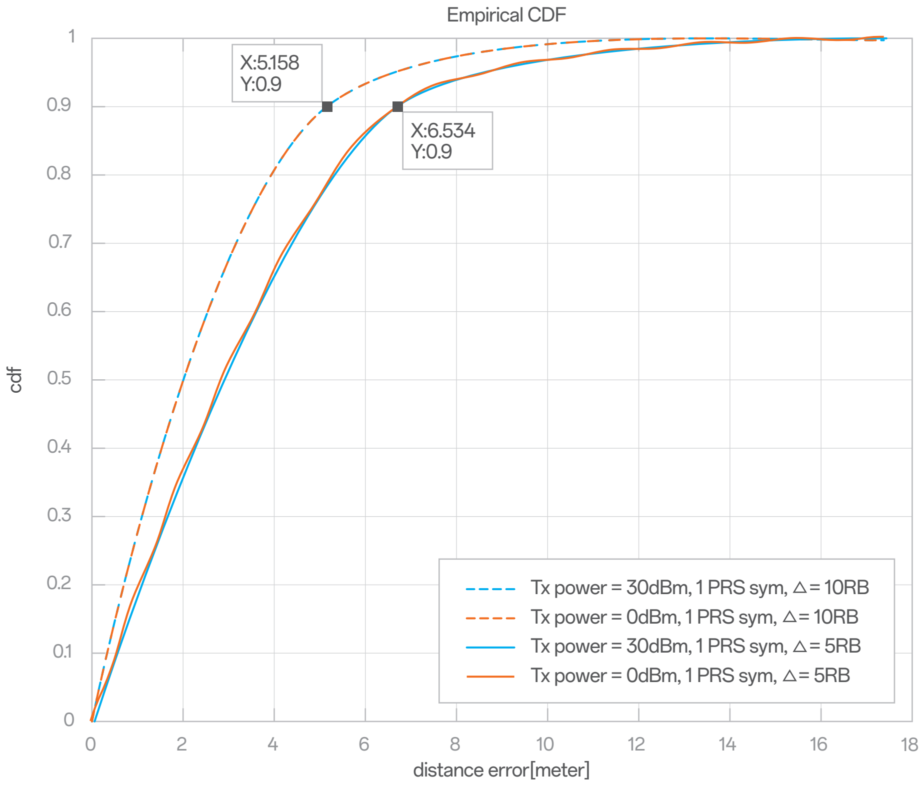

Figure 5.2-5 CDF of positioning error for phase difference based positioning

5.3 Requirements and challenges of lightweight protocol stacks

In the Ambient IoT system, the Ambient IoT device needs to collect energy in the environment (such as radio-frequency energy, luminous energy, thermal energy) before it is capable to work. Therefore, an Ambient IoT device keeps in 'power-off' state, i.e., out-of-service, before energy is obtained. This section will introduce the lightweight protocol stacks provided that the Ambient IoT device collects the RF energy from the radio wave sent by network.

In some use cases, islanding is observed in the deployment of Ambient IoT systems, where full coverage cannot be achieved. As a result, Ambient IoT devices are likely to be out-of-service due to lack of coverage, e.g., in logistics and warehouse scenarios.

Therefore, Ambient IoT devices are disconnected from network when there is no power source or out of coverage. Under such harsh conditions, smaller processing delay, lower memory consumption and more efficient data transmission schemes are required in the Ambient IoT system to enable faster data communication process.

5.3.1 State management

In traditional communication systems, service types of devices are complex, diverse, generally requiring service continuity and large data volume. According to whether there is data to be transmitted, network adopts different strategies in resource allocation and device management. In this regard, RRC states and NAS states are defined. When a UE is in RRC_IDLE state, it is essential to support mobility management and paging reception, while dedicated radio resources are not allocated for devices since there is no requirement of data transmission. When a UE goes into RRC_CONNECTED state, dedicated resources shall be configured by network in order to perform uplink and downlink data transmission. For subscribed users, NAS procedure is used by the core network to facilitate management, while RRC procedure is used by base stations.

Considering the characteristics of small memory, low processing capacity, battery-less, small data transmission and massive deployment, traditional multiple-layered protocol stack and complicated state management are no longer suitable for Ambient IoT devices.

For logistics and warehouse scenarios, complicated state management and transition procedures are not needed for devices that only needs to send single-packet data. Therefore, state-less concept is more beneficial for efficient small data transmission, which is also helpful to reduce the cost and complexity.

5.3.2 Lightweight protocol stack and efficient data transmission

The massive deployment of Ambient IoT devices makes the allocation of IP address one of the bottlenecks. The potential solution is to support non-IP data transmission which can not only simplify the data communication process, but also avoid unnecessary session management procedure.

In traditional communication systems, with the assumption that devices are with sufficient power, multi-layer protocol stack is defined to realize functional modularization. For example, SDAP is used to map QoS flow to DRBs. PDCP is used for header compression, data security, data delivery, etc. RLC realizes ARQ, data segmentation etc. MAC is for data multiplexing and de-multiplexing. Modularized multi-layer protocol stack is designed for diverse QoS requirements, complicated service types and large amount data transmission.

In Ambient IoT communication, due to the dependence on power supply and the limitation of device capacity (such as small memory and low calculation capability), lightweight protocol stack shall be designed to reduce the power consumption and computation complexity. In addition, small-volume, infrequent and delay-insensitive data is supposed to be supported by Ambient IoT devices. According to the above requirements and characteristics, flattening and sinking protocol stack is worth considering. Meanwhile, integration of control plane and user plane can further reduce the complexity of UE and accelerate the procedure of data transmission.

In addition, Ambient IoT devices can simplify the protocol stack structure adaptively according to different use cases. The demand for data transmission for Ambient IoT devices is relatively small. For example, in the warehouse and logistics scenario, the Ambient IoT device only needs to report its identification or collected information. Hence complicated protocol stack becomes unnecessary. For this kind of Ambient IoT device requiring simple transmission of its own state information, session management is not needed except for mobility management. For the transmission of small data such as reporting its own state, data transmission can be simply realized via mobility management stratum. Considering the different requirements of mobility, we can further study how to reduce the protocol stack on mobility management.

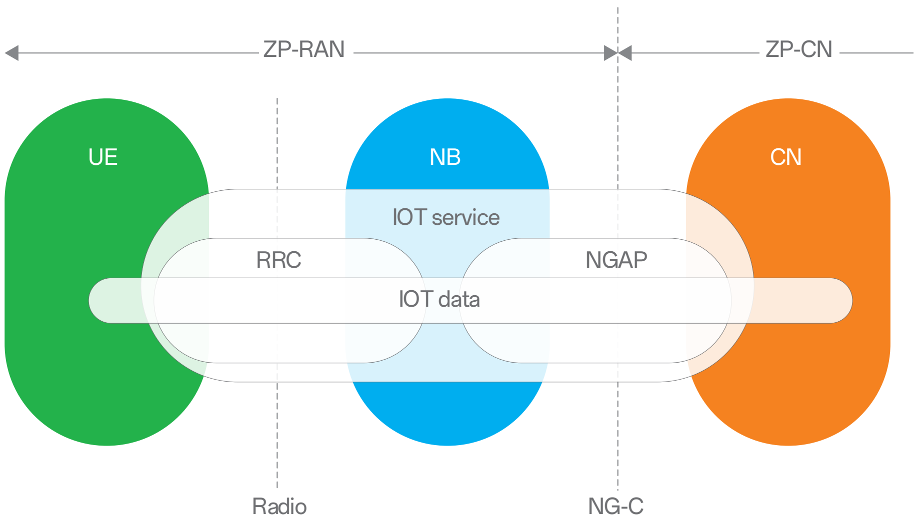

Figure 5.3-1 Lightweight protocol stack

Data transmission can be carried out based on non-state transition and non-dedicated bearer. The identification of Ambient IoT devices can be used for data receiving and forwarding, which will further simplify the data transmission procedure and achieve efficient data transmission.

Furthermore, various service types exist in the Ambient IoT system, such as logistics, warehouse, smart wearables, etc. Different service types may have different requirements on protocol stack for data transmission. To be specific, in logistics or warehouse scenario, data segmentation and (de-)multiplexing are not needed since the data amount is extremely small, single packet data transmission is expected, and the time interval of data traffic is long. Another example is smart wearable where data has the characteristics of continuous transmission, so it is necessary to consider sequential delivery of data packets.

Therefore, flexible and adaptive protocol stack is promising for the Ambient IoT system.

5.3.3 Mobility management

For different scenarios with different UE mobility characteristics and service QoS requirements, the mobility requirements of Ambient IoT devices are different. For most of scenarios, such as industrial wireless sensing, smart home, warehouse, etc., Ambient IoT devices are generally stationary where no mobility requirements are observed.

However, mobility management is essential for scenarios such as logistics, tracking, manufacturing monitoring. As an example, on a production line, the network needs to communicate frequently with mobile Ambient IoT devices. Compared with the traditional NR system, if there is no delay requirement and lossless requirement, mobility management with limited functions is enough.

In conventional communication systems, mobility can be controlled by either UE or network. Network-based mobility can guarantee data continuity. UE-based mobility can realize load balancing and enable proper cell selection. No matter which kind of mobility, the mobility management is completed in real time based on the measurement results of downlink reference signal transmitted by the network.

In Ambient IoT communication, devices may be out-of-service easily due to unstable power supply. Therefore, it is difficult to get location information for mobility management as in traditional communication systems, e.g., with periodic location updating.

Therefore, the requirements on mobility management for Ambient IoT devices needs to be investigated and how to execute necessary mobility management needs further study.

5.4 The requirements and challenges of lightweight security mechanisms

Similar as in other IoT scenarios, trusted access and secure transmission remain important for Ambient IoT. However, due to the extremely limited hardware and software capabilities, very small memory capacity, ultra-low power consumption and the dependence on external power supply, it is difficult for Ambient IoT devices to use complex security mechanisms as in LTE or NR. Therefore, a lightweight security mechanism suitable for Ambient IoT needs to be studied.

5.4.1 Trusted access and secure transmission for resource-limited device

The value security and trustworthiness of networks and devices will be highly recognized in 6G era. For personal devices, smart home devices, or industry devices, trusted access and secure transmission are expected when performing Ambient IoT communication.

The security mechanism in the 4G/5G era guarantees the above two security requirements[6][7] :

1) In order to ensure trusted access, the terminal side uses the pre-stored 256-bit root key K in the USIM card to calculate the authentication vector, IK and CK, using the f1-f5 function. Based on the authentication vector, the terminal and the network are mutually authenticated during the authentication process.

2) In order to ensure secure transmission, the terminal uses the KDF function, IK and CK in the ME to generate dozens of secret keys according to the requirements of different communication scenarios, and use these secret keys to perform operations to ensure the confidentiality and integrity of the data and signaling transmission.

However, in the Ambient IoT scenario, the computing and transmission resources supported by Ambient IoT devices are very limited. The traditional security mechanism is challenging for Ambient IoT devices due to resource constraints. It is necessary to research on how to provide trusted access and secure transmission under limited terminal resource conditions.

5.4.2 The security requirements of low cost and distributed scenario

Ambient IoT communication needs to support uplink data transmission, such as reporting information from Ambient IoT devices themselves or collecting information, which can be initiated by devices or based on control commands from network devices.

- Based on these two characteristics, the security threats of Ambient IoT can be divided into:

Downlink threat: false trigger

If a fake base station mis-triggers an Ambient IoT device to perform uplink data transmission, or a forged trigger signaling mis-triggers an Ambient IoT device to perform uplink data transmission, the possible harm may not only lead to waste of transmission resources and energy, but also cause data leakage or even user privacy disclosure.

Uplink threat: data leakage

If the uplink transmission data is eavesdropped or leaked, malicious attackers may obtain sensitive data or personal privacy data, which not only compromises the rights of the data owner, but also may cause compliance risks or legal risks for business operators or network operators.

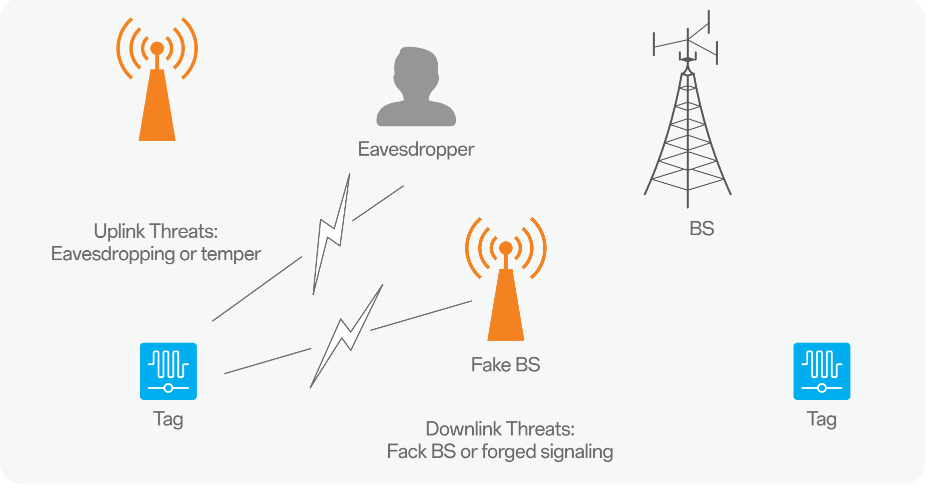

Figure 5.4-1 Security threats of Ambient IoT

The advantages of Ambient IoT devices are small size, light weight, low cost thus there is a wide range of application scenarios. Ambient IoT can be widely used in scenarios such as smart homes, logistics, manufacturing, personal wearable, etc., providing trillions of links for the Internet of Things.

- Therefore, the security requirements for Ambient IoT can be divided into:

Low-cost security requirements	In the Ambient IoT scenario, terminal equipment tends to be extremely simplified, with extremely low power consumption, and the cost, protocol stack and computing capability will be extremely reduced compared with current terminals. Therefore, it is necessary to research on the low-cost trusted access and secure transmission schemes that are compatible with extremely low-complexity terminal capabilities. From the terminal side, it is necessary to simplify the authentication calculation, the key management scheme, confidentiality and integrity protection calculations.
The requirements of distributed/scenario-diversified authentication and authorization	For logistics/manufacturing and other industry scenarios, Ambient IoT devices are connected within a specific factory area, which needs distributed authentication. Meanwhile, the business authorization for different scenarios as mentioned above shall be considered.

5.4.3 Possible security way forward for Ambient IoT

Facing the massive number of links and devices for the 6G Internet of Things, efficient distributed authentication and authorization need to be redesigned on the current centralized trust mechanism to ensure trusted identity management, flexible authorization and distributed authentication. Block chain is a feasible technology choice, meanwhile the infrastructure construction and ecosystem maturity are required to support multi-scenarios, multi-services, and multi-users trusted security mechanisms.

For Ambient IoT devices, trusted identity management and reliable secure transmission are mandatory to ensure rights and protections for business, networks, and users. It is necessary to consider the characteristics of ultra-low cost and ultra-low complexity in order to optimize the transmission security mechanism based on traditional security mechanisms, study the hierarchical protection mechanism of data transmission, and research on the enhanced security scheme that combines the physical layer and the transport layer.

5.5 Requirements and challenges to simplify network architecture

On the one hand, in many Ambient IoT scenarios, it is required for the network to be able to manage the Ambient IoT devices flexibly and efficiently, so as to enable and guarantee the realization of network functions (such as remote control, remote positioning and environmental monitoring) and facilitate the operation of Ambient IoT business. On the other hand, it is difficult to reuse the existing complex network architecture for Ambient IoT devices with minimal terminal capacity, very low power requirements and dependence on wireless power. Therefore, a simplified network architecture suitable for Ambient IoT needs to be studied.

5.5.1 Requirements to the simplify network architecture

With the increase in the number of users and the use of a large number of IoT devices, the network scale has been rapidly expanded, and business requirements have also shown diversified characteristics, which has resulted that network architectures become more and more complex. However, the existing complex network architecture is no longer adapted to the characteristics of Ambient IoT. The main reasons are as follows:

1) Complex network architecture will bring high operating costs to Ambient IoT, thus hindering the development of Ambient IoT.

2) Complex network architecture will also affect the power consumption of Ambient IoT devices, which brings new challenges.

3) The complex network architecture also makes the network deployment complicated and inflexible, which is not conducive to deploy Ambient IoT networks in a simple and rapid way.

In order to reduce network deployment costs, power consumption, and operating costs, a simplified network architecture is required to be considered for the network architecture of Ambient IoT. The simplified network architecture can simplify the types of network elements and combine network functions, making the deployment of network elements meet the requirements of Ambient IoT. Furthermore, the interface protocols between different network element types are also as simple as possible.

The following sections describe the characteristics of a network architecture suitable for Ambient IoT.

5.5.2 Support of simplified controlling signaling or transport plane

First of all, Ambient IoT does not require personalized QoS requirements, and signaling interaction is greatly reduced. For small data that needs to be sent, it can be sent in the mobility management procedure, so that it can reduce the interactive signaling for establishment of separate data channels.

Alternatively, if the default destination data center is configured at the Ambient IoT device, the Ambient IoT device can send in a stateless manner, and then send uplink data only when triggered by the network. The network can establish a dedicated data channel for Ambient IoT devices or services, which can avoid the establishment of a dedicated Ambient IoT data channel for each terminal.

In many cases, Ambient IoT only requires simple partial communication. In order to achieve such a function, a simple Non-Access-Stratum layer processing functions can be deployed in the base station, so that integrated communication with the air interface can be realized.

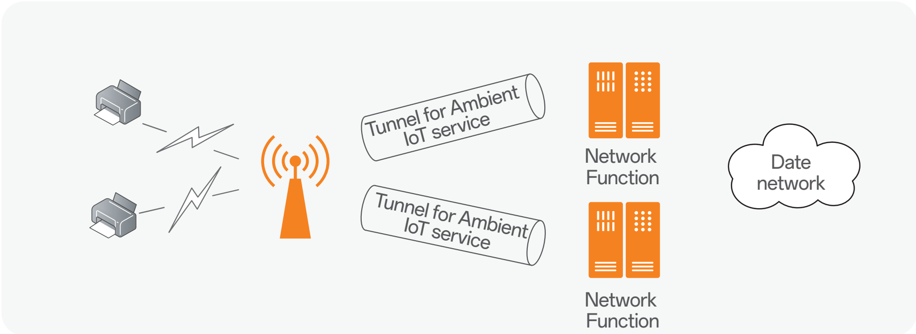

Figure 5.5-1 Simplified tunnel for Ambient IoT

5.5.3 Network architecture supporting hierarchical control

Ambient IoT devices can be used in logistics and warehouse. Due to limited power consumption of Ambient IoT devices, a hierarchical network architecture can be adopted. For example, the Ambient IoT device first sends the data to a certain data cache point in logistics or warehouse (data cache points can be installed or deployed in logistics vehicles or inside the warehouse), and the data cache points in logistics or warehouse are periodically or quantitatively reported with the data sent by the Ambient IoT device to the network. For downlink data, the network can also first send the data to a data cache point in logistics or warehousing for buffering, and then the data cache point can send the downlink data to a group of Ambient IoT devices at a fixed time or via a paging triggering.

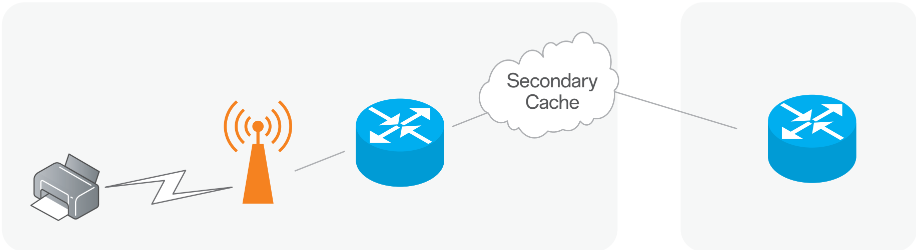

Figure 5.5-2 Network architecture supporting hierarchical control

5.5.4 Support flexible and efficient network selection function

Ambient IoT is mainly used in industrial sensor networks, logistics and smart homes. Therefore, Ambient IoT can ignore complex network environments such as roaming scenarios, and the demand for network selection is weakened. In this regard, the Ambient IoT device can perform flexible and efficient network selection functions to minimize the power consumption.

5.6 References

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STANDARDIZATION AND FUTURE TRENDS OF AMBIENT IOT

06

6.1 Industry status and standardization progress of Ambient IoT

6.1.1 Industry status of Ambient IoT

As mentioned earlier, there are clear and extensive application scenarios and urgent market demands for the Ambient IoT technology in the industry. However, there is currently no comprehensive Ambient IoT standard that can address the requirements of multiple scenarios. Prior to this, both the industry and academia have made many efforts to meet the application requirements of some scenarios. Next, we will introduce the current standardization activities and industry status of Ambient IoT.

RFID

RFID (Radio Frequency Identification) is a technology that uses radio frequency for contactless bidirectional data communication. A typical RFID system includes electronic tags, readers, and application systems. The electronic tags store relevant information about objects, while the reader is responsible for reading from and writing to the tags, and the application system is used to process and manage this information.

RFID, with the help of RF energy harvesting and ultra-low-power backscatter communication technology, has realized ultra-low complexity and ultra-low cost RFID tags. Currently, RFID technology is widely used in logistics, retail, manufacturing, healthcare, transportation, and other fields. Its application helps improve efficiency, reduce errors, and lower costs.

However, RFID also has some technical limitations, preventing its application in more scenarios. For example, in the process of backscatter communication, the carrier signal transmitted by the RFID reader and the signal reflected by the RFID tag are in the same channel, resulting in full-duplex interference between them. This limits the communication distance of the RFID system, generally not exceeding 10 meters, restricting its usability in various work environments. Additionally, the RFID protocol design greatly simplifies the complexity of RFID tag for system access, but it also limits the capacity of the RFID system, with a limited number of RFID tags that can be simultaneously accessed by the system. Finally, RFID systems are typical point-to-point communication systems that lack flexible and effective networking capability, leading to limitation of working efficiency in real life applications. For example, for the logistics and warehousing scenario, the efficiency and reliability of inventory via RFID tags still need to be improved.

EnOcean

EnOcean is another wireless communication system based on energy harvesting technology, particularly suitable for smart homes and building automation fields, such as wireless control for lighting fixtures. EnOcean technology supports ultra-low-power module operation and can self-power by collecting energy from the environment (such as mechanical energy, light energy, thermal energy, etc.), thus operating without batteries. This energy harvesting capability makes maintenance simple or even unnecessary, especially suitable for applications where power sources are difficult to replace.

EnOcean's communication protocol design is streamlined, employing a communication mechanism without the need for handshaking, making the communication process efficient and extremely low-power. In a typical EnOcean communication system, IoT devices act merely as transmitters. After collecting environmental energy, the devices can send sensor data and control signals to receivers. Receivers typically include gateways powered by cables, switch devices, control devices, etc. EnOcean data transmission uses a subtelegrams mechanism, where IoT devices repetitively send data packets to ensure proper reception by receivers and to prevent interference with other IoT devices.

EnOcean technology has obtained certification from the International Standards Organization ISO/IEC, including specifications for the physical layer, data link layer, and network layer.

Due to the design of the EnOcean protocol, which makes it more suitable for unidirectional control scenarios, its range of application scenarios is somewhat limited.

Ambient IoT based on existing standards such as Bluetooth, LoRa, etc.

In addition to the aforementioned Ambient IoT standards for specific scenarios, there are also explorations based on existing standards (such as Bluetooth, LoRa, WiFi, etc.) driven by urgent industry demands.

In these explorations, Ambient IoT devices communicate based on current protocols (such as Bluetooth, LoRa, etc.), and in different application scenarios, these devices can utilize energy sources like solar energy, thermal energy, etc., for energy harvesting to obtain the required energy for communication. Although some successful practices have been achieved in individual application scenarios, the design of these protocols does not specifically optimize for ultra-low power communication targeting the extremely low energy density of ambient energy. Therefore, in practical use, either larger ambient energy harvesting modules need to be equipped for the devices to collect sufficient ambient energy, or the communication frequency of Ambient IoT devices needs to be restricted to reduce total energy consumption. Consequently, the application scenarios for such Ambient IoT devices are also very limited.

6.1.2 Standardization progress of Ambient IoT technology

In order to meet the demands of the industry, the two major global standardization organizations, 3GPP and IEEE, are currently conducting research and standardization efforts for Ambient IoT technology.

Standardization progress of Ambient IoT technology in 3GPP

Over the past few decades, 3GPP has standardized a series of wireless communication technologies, including GSM, WCDMA, LTE, NR, etc., greatly meeting people's needs in areas such as voice calls, mobile internet, and effectively promoting the development of society and the improvement of people's living standards. In the past decade, 3GPP has also standardized technologies such as MTC, NB-IoT, and RedCap, specifically targeting IoT requirements, and has achieved certain commercial success. However, 3GPP has not yet standardized a solution that meets the requirements of Ambient IoT-related scenarios.

In past standardization practices, 3GPP has accumulated a wealth of technologies and solutions related to low-power communication, low-complexity communication, massive connectivity, etc. The industry and academia have also made fruitful achievements in various environmental energy harvesting technologies (such as RF energy harvesting, micro photovoltaic energy harvesting, temperature difference-based thermal energy harvesting, etc.). Therefore, the timing for 3GPP to conduct research and standardization of A,bient IoT technology has matured.

Starting from May 2021, OPPO took the lead in submitting a standardization proposal for Ambient IoT to 3GPP SA1 [1-7], suggesting that 3GPP study the application scenarios and technical requirements of Ambient IoT. This proposal was approved at the SA1#97 meeting in February 2022 [8], marking the beginning of 3GPP's research on Ambient IoT.

Below, we will introduce the standardization progress of 3GPP Ambient IoT:

- In February 2022, at the 3GPP SA1#97 meeting, the initiation of research on Ambient IoT proposed by OPPO was approved. As of now, this project has completed all research and standardization work. The project has studied and agreed upon over 30 application scenarios and their technical requirements for Ambient IoT [9], and has developed relevant technical specifications [10].
- In September 2022, at the 3GPP RAN#97 meeting, agreement was reached for the study item (SI) on Ambient IoT at the RAN level proposed by Huawei. This research project primarily focuses on studying deployment scenarios and network topologies of Ambient IoT, types of devices, design goals, etc. As of now, this SI has also completed all research work and produced a technical report [11].
- In November 2023, at the SA#102 meeting, a SI on the network architecture of Ambient IoT, led by Huawei and OPPO was agreed [12]. This SI will formally commence related research and standardization work from February 2024.
- In November 2023, at the RAN#102 meeting, a SI on RAN for Ambient IoT, led by China Mobile, Huawei, and T-mobile [13] was approved. This research project will also formally commence related research and standardization work from February 2024.

Support for cellular-based Ambient IoT offers at least the following advantages:

- Cellular communication networks have achieved wide-area seamless coverage in major regions globally, thereby possessing the potential to provide wide-area coverage for Ambient IoT networks.
- Within cellular networks, there are not only base station equipment and relay nodes but also numerous intelligent terminal devices. These devices and nodes can serve as power supply nodes and communication nodes for Ambient IoT devices.
- Operators possess the high-quality sub-1 GHz frequency band, with minimal loss in the low-frequency bands. This is advantageous not only for enhancing communication distances but also for extending wireless power supply distances, thus enabling better coverage for Ambient IoT networks.
- Cellular networks possess strong device management and mobility management capabilities, supporting IoT communication in complex scenarios (such as logistics).

Standardization progress of Ambient IoT technology in IEEE

Over the past 20 years, IEEE 802 work group (WG) has standardized a series of WLAN communication standards and achieved significant commercial success. Through continuous technological updates and standard iterations, WiFi standards have achieved characteristics such as high speed, large capacity, and low latency, effectively meeting the demand for high-speed wireless local area communication in scenarios such as homes, offices, and shopping malls. In past practices, WiFi standards such as 802.11b/n have also been widely applied in IoT scenarios such as industrial monitoring and industrial automation. In response to IoT communication requirements, 802.11 has specifically developed 802.11ah to achieve lower device costs, a greater number of connections, lower power consumption, and longer battery life. However, IEEE 802 still lacks a standard for Ambient IoT communication.

Research and standardization of Ambient IoT technology within IEEE 802 offers the following advantages:

- The widespread deployment of WLAN infrastructure provides a solid foundation for the deployment of Ambient IoT networks.
- Free frequency bands can reduce the deployment and operation costs of Ambient IoT.
- IEEE 802 focuses on short-range and local communication scenarios such as homes, smart wearables, and industrial local communication, better matching the requirements of many scenarios in Ambient IoT technology.
- 802 WG has already standardized related technologies such as 802.11ah and 802.11ba, which can serve as the basis for standardizing Ambient IoT.

Based on the considerations mentioned above, in May 2022, OPPO submitted a standardization proposal for Ambient IoT to IEEE 802.11 [14], proposing to study the application scenarios, technical requirements, and key technologies of Ambient IoT. This proposal was approved at the May 2022 IEEE meeting, initiating the research process of IEEE 802.11 on Ambient IoT.

Below, we will introduce the standardization progress of IEEE 802.11 Ambient IoT:

- At the May 2022 IEEE meeting, approval was granted for the Technical Interest Group (TIG) on Ambient IoT initiated by OPPO, establishing the AMbient Power-enabled (AMP) TIG. During the TIG phase, research on application scenarios, technical requirements, key technologies, etc., for Ambient IoT was completed [15]. To verify the technical feasibility, the TIG phase also showcased multiple demos provided by many companies [16].
- At the March 2023 IEEE meeting, approval was given for the establishment of a Study Group for the IEEE 802.11 Ambient IoT proposed by companies such as OPPO [17]. During the SG phase, further research was conducted on deployment methods, key technologies, and operating modes of Ambient IoT. At the IEEE meeting in November 2023, approval was granted for the PAR [18] and CSD texts [19] of the Task Group stage. In March 2024, the 802.11bp Task group (TG) was formally established, signaling that the project will enter the Task Group phase in the first half of 2024, officially commencing the development of Ambient IoT standard specifications.

6.2 The future trends of Ambient IoT

6G technology is in the ascendant. At present, many kinds of candidate technologies for 6G have been widely developed by the industry. As a new communication technology, Ambient IoT is expected to integrate with other 6G candidate technologies to build a green, energy-efficient, intelligent and efficient mobile communication network.

6.2.1 Integration of Ambient IoT and symbiotic radio

In a typical AmBC (Ambient Backscatter Communications) system, Ambient IoT devices can use radio waves in space to realize backscatter communication[20]. As shown in Figure 6.2-1, when a router and an intelligent device in a primary communication system is communicating, Ambient IoT device backscatters the downlink signal sent by the router in order to transmit information to the reader. A secondary communication system supported by backscatter communication technology is formed by the Ambient IoT device and the reader. Because of its potential value, backscatter communication was rated as one of the top ten breakthrough technologies in the 2016 MIT Technology Review.

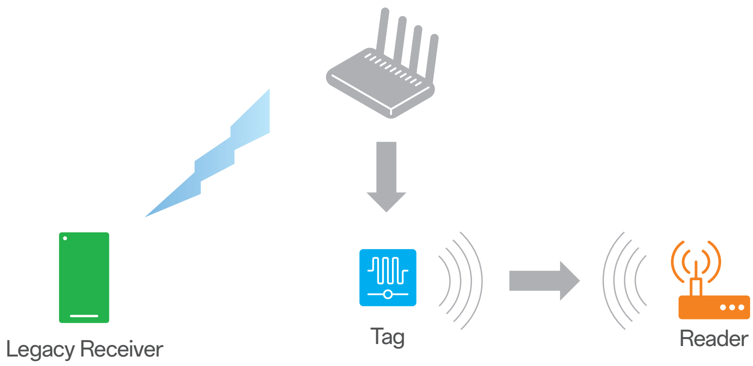

Figure 6.2-1 Illustration of Ambient Backscatter Communications system

However, in the above AmBC system, because the same spectrum is used by the primary communication system and the secondary communication system, the communication of the secondary communication system will interfere the primary communication system. That is, the backscatter signal of the Ambient IoT device will be mixed into the signal received by the receiver of the primary communication system and degrade its decoding performance. Therefore, although the use of backscattering benefits the secondary communication system, it may sacrifice the performance of the primary communication system.

In order to solve the above issue, the concept of symbiotic radio is proposed[21] Symbiotic radio works on the basis of environmental backscattering through good coordination between the primary system and the secondary communication system. It not only eliminates the interference from the secondary communication system to the primary system, but also converts the backscatter signal into a signal which is beneficial to the primary communication system.

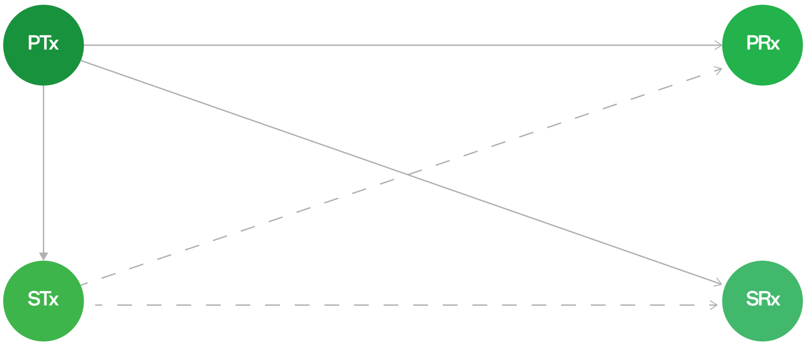

Figure 6.2-2 Symbiotic radio

As shown in Figure 6.2-2, a symbiotic radio system includes the primary communication system and the secondary communication system. The primary transmitter PTx and the primary receiver PRx constitute the primary communication system while the secondary transmitter STx and the secondary receiver SRx constitute the secondary communication system. STx realizes backscattering using signals transmitted by PTx. In order to enable symbiotic radio, one of the most important things is that the chip width Cp of the signal backscattered from the secondary communication system and the chip width Cs of the primary communication system need to satisfy a K-fold relationship, namely Cp=K*Cs. Therefore, the backscattering signal does not change in the duration corresponding to K chips of the primary communication system. Thus, when the primary communication system performs coherent demodulation, the backscatter signal from the secondary communication system is equivalent to a multipath signal for the primary communication system[22]. With such constraints, it not only eliminates the interfere from the secondary communication system, but also improves the performance of the primary communication system by providing multipath signals[23]. Since such kind of relationship of between the primary communication system and the secondary communication system is similar to biological symbiosis, the communication system model is named symbiotic radio.

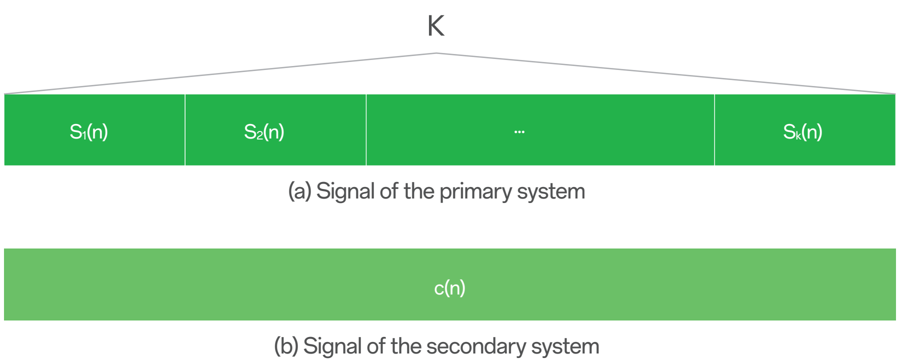

Figure 6.2-3 Relationship between the signals from the primary communication system and the secondary communication system

Symbiotic radio enables Ambient IoT to share the spectrum of traditional communication and coexist well with traditional communication on the same spectrum. Therefore, symbiotic radio is expected to become an important manner to realize Ambient IoT communication.

6.2.2 Integration of Ambient IoT and ISAC (Integrated Sensing And Communication)

While transmitting information in wireless channels, ISAC can realize the sensing functions of target positioning, detection, imaging and recognition by actively recognizing and analyzing the characteristics of the channel and using wireless signals to sense the physical characteristics of the surrounding environment, so as to excavate communication capabilities and enhance user experience. In terms of hardware architecture, a great challenge for the ISAC system is to adapt to high-precision sensing requirements. Thus, it will greatly increase the dynamic range and complexity of hardware system. How to design a green and energy-saving hardware system architecture that meets the two-way requirements of ISAC is one of the important challenges in the future [24].

In ISAC, it is necessary to sense various users and environmental backgrounds. Usually, these tasks are done with the help of special sensors. However, these special sensors often need external power source to run. Because the energy stored by the battery is limited, the battery either needs to be charged or replaced during the use of the equipment, which is not only inconvenient and costly, but also impossible to implement in some deployments (extreme environments such as high temperature, low temperature, radiation, etc.).

The integration of Ambient IoT technology (mainly using energy harvesting and ultra-low power communication) and ISAC can significantly improve the energy efficiency and meet the green energy saving goal of ISAC [25]. On the one hand, energy harvesting technology can obtain energy from the surrounding environment and fundamentally eliminate the dependence on batteries. On the other hand, when communicating based on ultra-low power communication technology, only microwatt power consumption is required to achieve extremely low power consumption. At present, backscattering technology has been applied in many fields, such as using radio frequency backscattering for food and liquid quality test [26], using battery-free mobile phone for communication [27], using backscattering assisted vehicle network[21], using backscattering for underwater monitoring [28], using visible backscattering for gesture sensing [29], etc.

Ambient IoT also provides an effective means for ISAC. An Ambient IoT unit is installed on the target object, which can trigger the Ambient IoT communication process when the network triggers the sensing signaling of the target object, so that the information of the target object is reported to the network side through the Ambient IoT communication mode, realizing accurate sensing function.

In addition, the energy harvesting mode can also be used to reflect the environmental characteristics. At present, there has been research on the sensing of the surrounding environment based on energy harvesting signal. Therefore, the energy harvesting module in Ambient IoT can be used as a virtual sensor to detect the surrounding environment. Based on this, the industry has extended the application of signals used for energy harvesting [30], which can be used not only for circuit driving but also for sensing through energy harvesting signals. For example, kinetic-powered wearable IoTs are able to detect and count the user’s steps, as the energy harvester generates distinguishable peaks in the energy harvesting signal each time the leg hits the ground [31]. Similarly, a thermoelectric energy harvester is able to detect any changes in surface temperature simply from the variations in the generated energy harvesting signal [32][33].

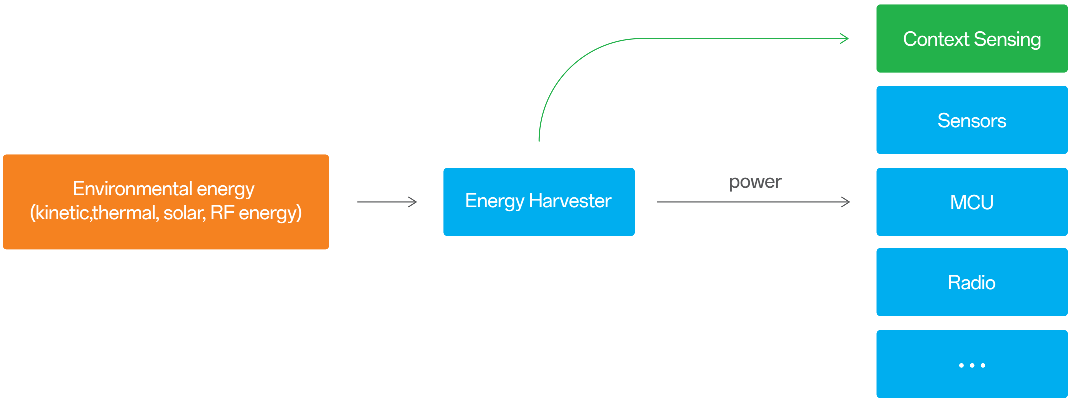

Figure 6.2-4 Application Extension of Energy Harvesting Signal

In recent years, the energy harvesting modes from kinetic, thermoelectric, solar, and RF energy harvesters have been demonstrated to detect a variety of contexts [30]. Irrespective of the type of energy source, there are two main approaches for sensing from energy harvesting signals. The first approach analyzes the patterns of the instantaneous power generated by the energy harvesting transducer, while the second approach analyzes the amount of the total energy accumulated in the storage over a specific period of time.

Typical applications of sensing based on energy acquisition signals [30] are shown in Table 6.2-1:

Table 6.2-1 Typical applications of sensing based on energy acquisition signals

Energy Harvesting Patterns	Typical applications	
Energy Harvesting from Kinetic energy	Human Activity Recognition (such as walking and running).	
	Transportation Mode Detection (such as car, bus, or train).	
	Estimation of Calorie Expenditure.	
	Step Counting.	
	HVAC (Heating Ventilation Air Conditioning) Airflow Monitoring, etc.	
Energy Harvesting from Thermoelectric energy	Water Flow Detection [34]	(harvests energy from the pipe's thermal gradient, i.e., the temperature difference between the pipe and the room temperature, when hot water flows through the pipe. The harvested thermal energy is used to wake up the sensor from deep sleep mode as well as to compensate battery energy expenditure.).
	Heat Appliance Monitoring.	
	Chemical Reaction Detection, etc.	
Energy Harvesting from Solar energy	Localization and Positioning, Gesture Recognition, Visible Light Communication, etc.	
Energy Harvesting from RF energy	RFID tags for integrated sensors	

The integration of Ambient IoT and ISAC can realize the integration of communication, sensing and energy transmission. On the one hand, battery-free and energy saving can be achieved through energy harvesting and ultra-low power communication technology, which is convenient for deployment in some complex environments. On the other hand, it can also sense the surrounding environment based on the energy harvesting module.

6.2.3 Integration of Ambient IoT and AL/ML

AI (Artificial Intelligence) is the simulation of human intelligence processes by computer system. It is usually defined as the science of making computers to perform tasks that require intelligence like humans [35]. ML (Machine Learning) is one of the most popular applications of AI, which can optimize system performance and reactions to environments by learning, inferring, fitting and categorizing from large amount of data. Generally, ML can be divided into supervised learning, unsupervised learning and reinforcement learning. Taking supervised learning as an example, where artificial neural networks (ANN) is a typical algorithm, the weighting coefficients between neural network nodes are trained based on set of prior data. When the training is converged, multi-layered neural network is able to identify and infer new data. In general, more essential characteristics can be learned by increasing the number of hidden layer nodes, which is beneficial to improve the accuracy in classification and prediction. Deep learning is achieved by this way. It is foreseen that AI technology can effectively improve system performance, reliability and adaptability. Currently, AI has been widely used in various fields to create more excellent operation efficiency.

For Ambient IoT system, terminals may experience more complicated and stringent communication conditions. In some scenarios such as logistics and product line detection, a large number of terminals need to communicate with network using limited channel resources, which brings challenges to coordinate the communication between terminals. In addition, it is not suitable to perform extra channel measurement or reporting procedure due to limited power of Ambient IoT devices. Without sufficient channel information, how to improve date transmission performance and perform access control effectively is another challenge. Therefore, AI technology can be considered to improve the performance of Ambient IoT system in these scenarios. Possible directions are listed as follows:

1: Optimizing communication strategy of Ambient IoT with AI/ML [36][37]

AI training model takes environment information, feedback information from network (e.g., whether the UL transmission is correctly received) and system performance indicators as inputs, and communication strategy at Ambient IoT devices as output, in order to optimize the operation strategy. For example, based on the training results, Ambient IoT devices can adaptively switch between operations such as energy collection, backscattering or active transmission with ultra- low power consumption, channel estimation and equalization etc. according to different environments. When communicating with network, the device can adjust time, data rate, power and other parameters with the help of AI in combination with environmental interference and its own power level. Reliability and robustness of the Ambient IoT system can be improved with the aid of AI.

Figure 6.2-5 Optimizing communication strategy of Ambient IoT device with AI/ML

2: Optimizing resource allocation method, access control and energy supplying strategy of network with AI/ML [38][39]

As an example, with the assistance of AI, Ambient IoT network nodes train resource allocation methods and wireless power supplying strategies under transmission conditions. The coverage can be enhanced by selecting appropriate node pairing strategy to ensure efficient energy collection and communication.

In addition, the performance of AI systems largely depends on sufficient data sources. Ambient IoT devices have the advantages of small size, low cost, low power consumption and are convenient for large-scale deployment. Therefore, a low-cost data collection scheme can be provided by Ambient IoT devices, which can be used to improve the performance of AI system. For example, in smart factory scenario, Ambient IoT devices are used to collect environmental information, such as temperature, humidity, pressure, motion attitude, vibration frequency, etc. With this kind of data, AI can predict the changes in advance, such as environment, working state, etc., in order to trigger warning or provide indication information for other intelligent devices. In the smart home scenario, Ambient IoT devices collect information such as the position of human body, daily living habits, temperature, light, etc. AI can be used to realize intelligent linkage between various home devices to make life more comfortable.

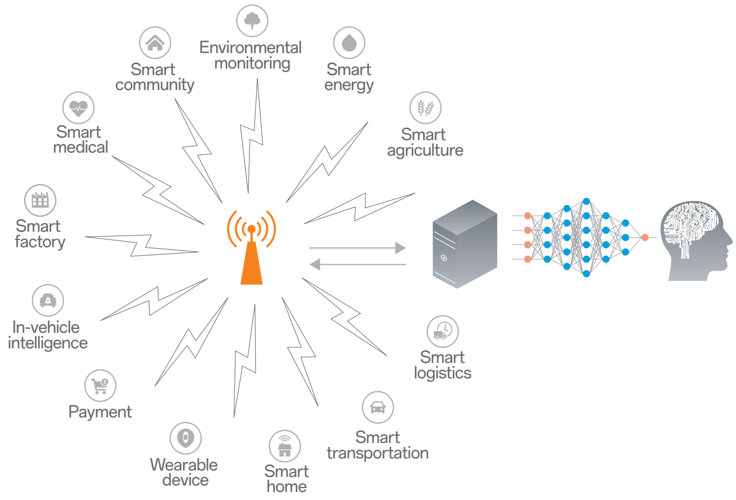

Figure 6.2-6 Low-cost data collection for AI by using Ambient IoT devices

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EPILOGUE

Time flies, and it has been over two years since the first edition of the "Zero Power Communication" white paper was released. Over the past two years, we have worked together with various industry partners to promote the research, standardization, and industrialization of such technology, and rename it as Ambient IoT technology based on its unique technical features. We have delved into the frontline of the industry to understand the real demands from all parties. Through our joint efforts with various parties, we are pleased to see that many industry players, including numerous operators, potential industry application parties, equipment vendors, and chip manufacturers, have shown strong interest in Ambient IoT technology. The industry is eagerly anticipating the rapid implementation and application of this technology. In response to industry demand, we have been working with all parties to promote the technical research and standardization of Ambient IoT technology in 3GPP and IEEE 802.11, and have made significant progress. We also showcased Ambient IoT tags at MWC 2023 and received widespread attention. This technology was also honored to be selected as one of the best inventions of 2023 by Time Magazine.

In the past two years of research and standardization practice, we have closely communicated with various industry partners about Ambient IoT technology. During this period, we have repeatedly re-examined the industry positioning and potential market value of Ambient IoT technology. We conducted multiple rounds of research on Ambient IoT application scenarios and worked with the industry to identify the most likely typical application scenarios for implementation. Through communication with all parties, we have further improved the technical framework and technical roadmap of Ambient IoT and deepened our understanding of its key technologies. In standardization discussions, for the convenience of technical exchange, industry parties have reached a consensus on the standardization naming of this technology—Ambient Power-enabled Internet of Things. Based on this, we realize the need to update the "Zero Power Communication" white paper to reflect these latest changes and developments.

We are pleased to see that the first edition of the "Zero Power Communication" white paper has become a bridge for us to meet many friends from the industry. Friends from various industries, universities, and research institutes from all over the world have come together with us after reading this white paper to jointly promote the standardization and industrialization of Ambient IoT technology. In this process, many friends and teachers have given us strong support and selfless assistance, for which we are grateful. We hope that the updated version of this white paper, titled "Ambient Power-enabled Internet of Things," can contribute to the development of our cause. We believe that through everyone's concerted efforts, the commercialization of the Ambient IoT is imminent, and it will play a positive role in improving social production efficiency and people's living standards.