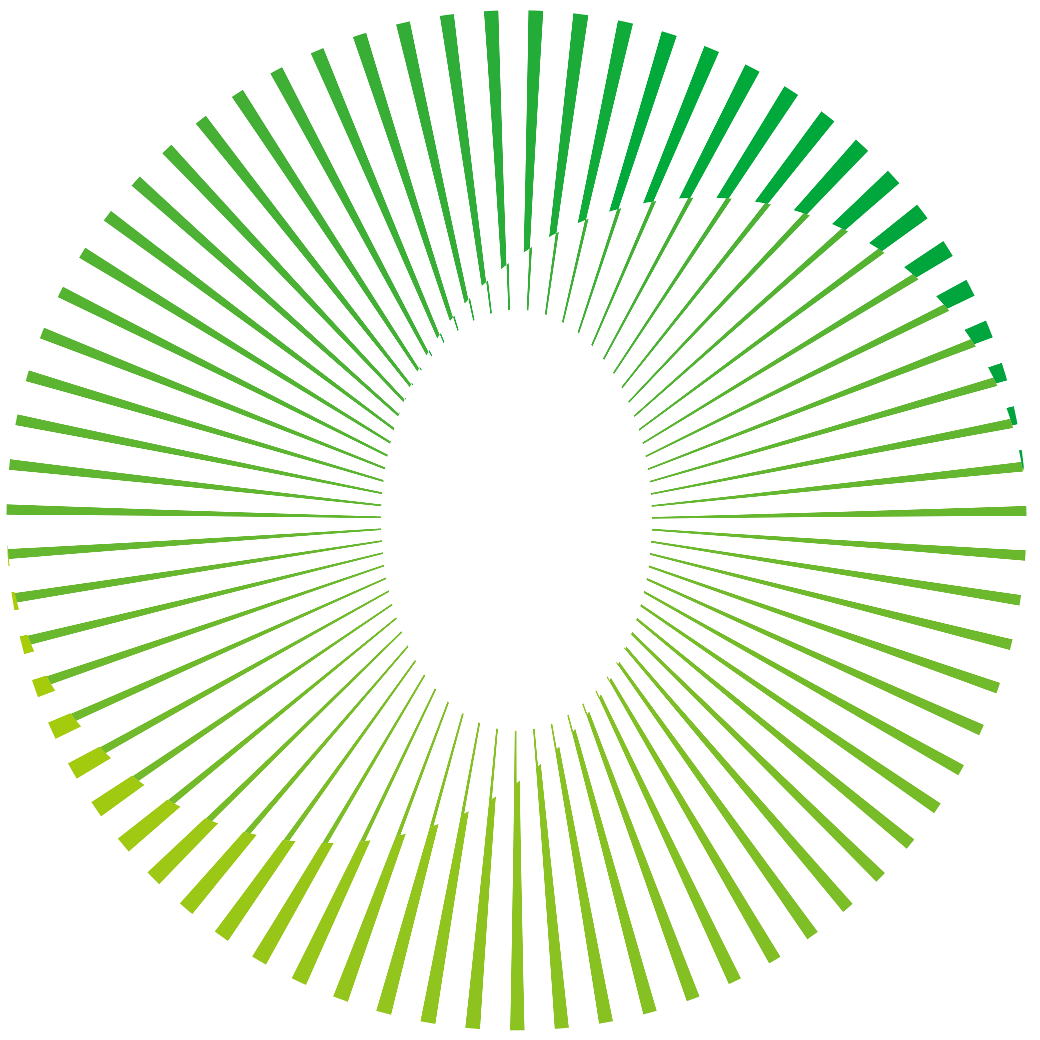

Zero-Power communication

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CONTENT

INTRODUCTION

In recent years, 3GPP have standardized series of technologies on IoT (Internet of Things), which achieves the design targets of low cost, low power consumption, massive connection and deep coverage. These IoT technologies can well meet the requirements of diverse scenarios. However, there are still many other scenarios that require the terminal to have ultra-low power consumption or even zero power consumption, ultra-low cost, very small size etc. With techniques such as RF power harvesting, backscattering and low power computing, zero power communication can well meet these new requirements. Due to its excellent characteristics, zero-power communication is expected to become one important candidate of next generation technology on Internet of Things.

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1.1 Recent progress of Internet of Things

Digital mobile communication has experienced 2G, 3G,4G and it is still continuing to evolve. Currently the 5th generation mobile network can well meet people's needs in voice communication, digital mobile communication and mobile broadband Internet communication. In the meantime, the demand for the internet of things has also been gradually risen with the development of society and economy. Technologies and standards related to the Internet of things (IoT) have been developed and evolved since 2010. Among them, 3GPP (3rd Generation Partnership Project) standardizes 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 decreased by the introduction of eDRX (enhanced Discontinuous Reception) and PSM (Power Saving Mode). At the same time, existing IoT solutions can also support a large number of terminals for simultaneous network accessing to meet the need of massive connection.

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 Internet of Things terminals, they meet the communication requirements of Internet of Things in many scenarios. However, there are still many situations where communication requirements cannot be satisfied with existing technologies, such as:

Harsh communication environment

Some scenarios of the Internet of things may face extreme environments such as high temperature, extremely low temperature, high humidity, high pressure, high radiation or high-speed movement. For example, there are hazardous circumstances in an ultra-high voltage power station, railway for high-speed moving trains, environmental monitoring in high-cold areas, industrial production lines and so on. In these scenarios, due to restrictions of the working environment of conventional power supplies, the existing Internet of things terminals will not work. In addition, maintenance of IoT devices (e.g., replacing batteries) becomes challenging under extreme conditions.

Requirements of ultra-small form factor of the IoT terminal

For some Internet of things communication scenarios, e.g., food traceability, commodity circulation and smart wearables, it requires the terminal to have an ultra- small size to facilitate application in these scenarios. For example, the IOT terminal used for commodity management in the circulation usually uses the form of electronic label and is embedded into the commodity packaging in a very small form factor. As another example, light-weight wearable devices can improve the user experience while meeting communication needs.

Requirements of ultra-low cost IoT communication

Many communication scenarios of the Internet of things require that the cost of the terminal of the Internet of things to be low enough to enhance its competitiveness compared with other alternative technologies. For examples in logistics or warehousing scenarios, in order to facilitate the management of a large number of goods in circulation, the terminal can be attached to each item in order to complete the accurate management of the whole logistics process through the communication between the terminal and the logistics communication network.

Therefore, for the Internet of things communication scenarios represented by the above ,it requires the terminals to fulfill the requirements of battery-free, ultra-low power consumption, very small size and ultra-low cost. The existing IoT technology cannot meet these requirements. How to solve these unsatisfied communication requirements of the Internet of things and better serve the economic and social development is a problem worthy of discussion and study.

1.3 Development vision of zero-power communication

Zero-power communication technology utilizes key techniques such as RF energy harvesting, backscattering communication and low-power computing. Zero-power communication obtains energy by harvesting radio waves in the space to drive the terminal. Therefore, the terminal can be battery-less without using conventional batteries, so it can effectively reduce the size and cost of the terminal. Furthermore, backscattering communication and low-power computing technologies make the terminal achieve an extremely simplified RF and baseband circuit structure, which can greatly reduce the terminal cost, terminal size and circuit energy consumption. Therefore, zero-power communication is expected to achieve battery-less terminals to meet the communication needs of the Internet of things with ultra-low power consumption, very small size and ultra-low cost.

Due to its good characteristic of battery-less, such kind of terminal is named zero-power terminal and the corresponding communication procedure is called zero-power communication.

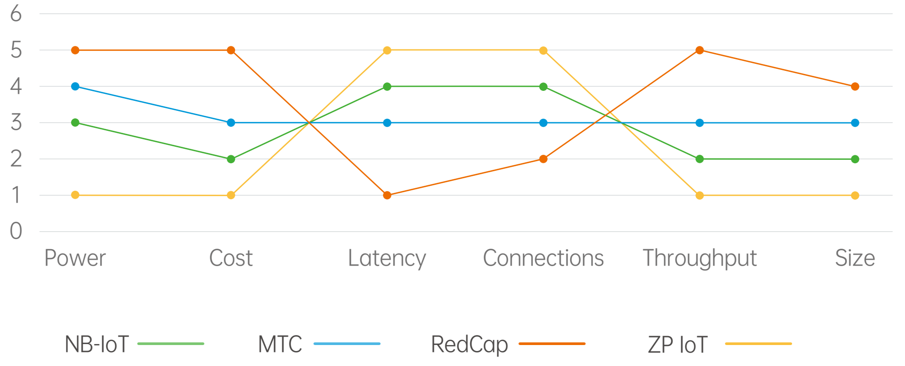

Figure 1.3-1 Comparison of IoT technologies

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

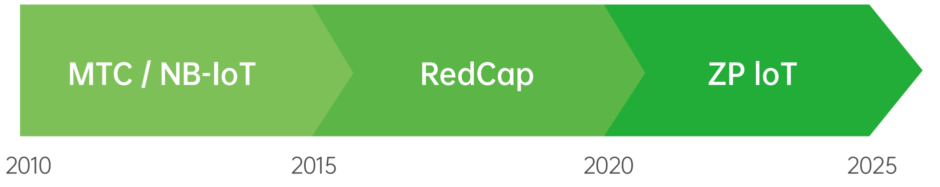

Figure 1.3-2 Development roadmap of Internet of things technology

To sum up, zero-power communication will be committed to meet the communication requirements that the 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 the Internet of things.

TYPICAL USE CASES OF ZERO-POWER COMMUNICATION

The outstanding technical advantage of zero-power communication is battery free. Due to the use of keytechnologies such as energy harvesting, backscattering communication, and low-power computing, the terminal can be battery-free and support extremely low hardware complexity. Therefore, zero-power communication can meet the requirements of ultra-low power consumption, extremely small size, and extremely low cost.

It can be predicted that zero-power technology will have significant advantages in a wide range of applications. For example, industrial wireless sensor network (IWSN) for vertical industries, smart transportation, smart logistics, smart warehousing, smart agriculture, smart cities, and energy field, as well as applications for individual consumers such as smart wearables, smart home and medical care, etc. In this section, we will select some of the scenarios to illustrate the potential application of zero-power communication.

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2.1 Industrial Wireless Sensor Network

IWSN has a wide range of applications, including building automation, industrial process automation, power facility automation, automatic meter reading and inventory management, environmental sensing, security, production line monitoring, etc. A large number of sensor nodes are often deployed in these application scenarios, and the sensor nodes are used for temperature and humidity monitoring, vibration monitoring, production line monitoring, industrial automation and numerical management, hazardous event monitoring, etc. Compact and low-cost sensor equipment is the key to realize large-scale deployment of IWSN. In order to meet technical challenges and meet the needs of various IWSN applications, it is necessary to follow the design objectives of low-cost and small sensor nodes.

In view of the ultra-low power consumption, extremely small size, and extremely low cost of the zero-power communication terminals, zero-power communication will have a wide range of potential application in the IWSN scenario. In particular, it should be pointed out that the characteristics of battery-free with zero-power communication terminals can also extend zero-power communication to application scenarios that cannot be covered by legacy Internet of Things communication technologies. For example, in some IWSN applications, industrial sensor nodes may be deployed in harsh environments and special location spaces, or even in extremely hazardous environments (such as high/low temperature, high-speed moving or rotation parts, high vibration conditions, humidity, etc.). In these application scenarios, on the one hand, due to the working environment, terminals driven by conventional battery may not work properly (restricted by the requirements of the physical and chemical characteristics of the battery). On the other hand, when using traditional terminals, the high network maintenance costs and even the limitations of the working environment would make network maintenance impossible to perform. Therefore, the existing terminals cannot meet the requirements in such application scenarios.

Applying zero-power communication technology in IWSN with energy harvesting and backscattering technologies, sensor nodes can achieve battery-free and ultra-low power consumption, which will greatly solve the limited battery life cycle problem of sensor nodes and greatly extend their service life. At the same time, the battery-free feature of zero-power communication will also greatly reduce the maintenance cost of sensor nodes and even achieve maintenance-free.

Therefore, the combination of zero-power communication and IWSN can greatly expand the application scenarios of IWSN, increase the service time of sensor nodes, and reduce deployment and maintenance costs.

- Some typical use cases for IWSN scenario are as follows:

Tire management

The zero-power terminal (equipped with corresponding sensors) is embedded in the tire, and the basic information of the tire (such as tire pressure, tire life, brand, factory, etc.) is collected and recorded by the terminal [1], so as to facilitate the manufacturing, after-sales and use management of the tire. The significant advantage of using a zero-power terminal is that data can be collected and recorded without damaging or removing the tire.

Railway Track monitoring

The zero-power terminal equipped with corresponding sensors is deployed under railway [2], and the sensors provide pressure, heat and other information of the track during and after a train run on the track.

Environmental Information Collection

Information is collected in some special environments (such as high temperature, high pressure, extreme cold, radiation, etc.). Such as ultra-high voltage stations, substations and other application environments.

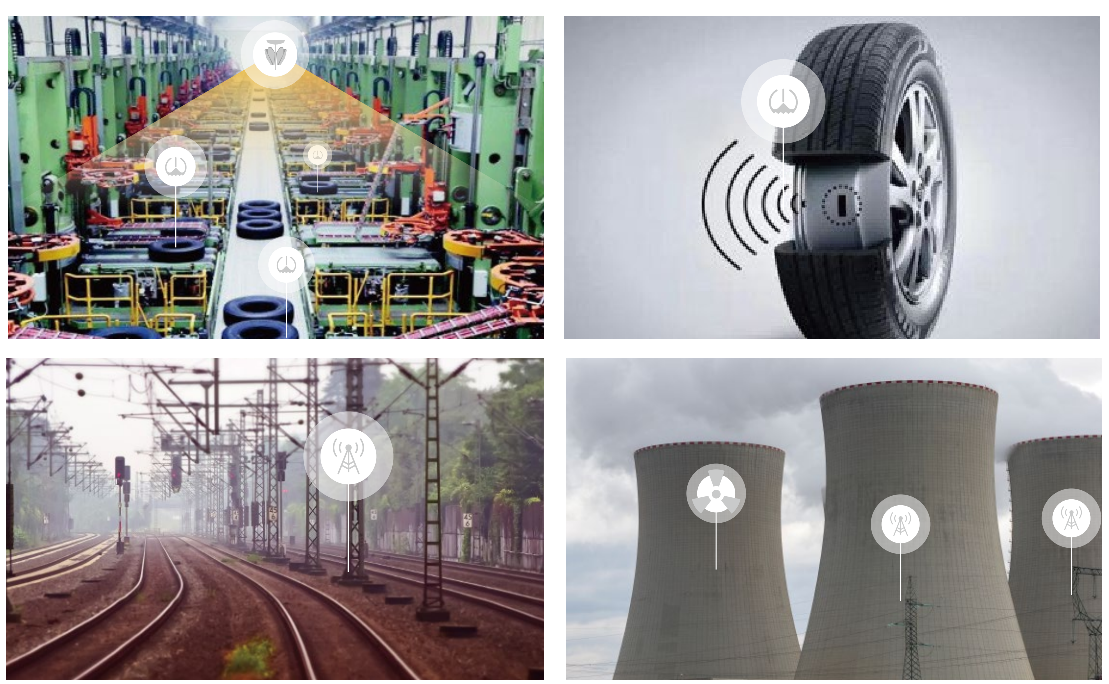

Figure 2.1-1 Application of Zero-power Technology in IWSN

- Typical requirements for IWSN scenario are as follows:

Terminal requirements:

The zero-power terminal is in the form of an electronic tag, which can be integrated with memory for data access or integrated with sensors for information collection. Since it is generally a large-scale application (each device will have a tag), the cost and power consumption of the tag need to be taken into account.

Tag size: extremely small size, convenient for large-scale application.
Tag type: paper tag and anti-metal tag.
Tag power consumption: the terminal power consumption is less than 1mw, battery free and maintenance free.
Working environment: It can match and work normally in special environments such as high temperature, high pressure, extreme cold, radiation, etc.
Communication distance:support communication in the range of tens of meters to hundreds of meters.

Network requirements:

Flexible deployment based on cellular network: Network equipment can be deployed in outdoor pole stations, indoor with DIS (Digital Indoor System) station spacing deployment, to provide basic coverage.
Coverage requirements: coverage distance requirements of a single station (indoor >30m, outdoor >100m).
Network security: authorization-based tag reading to protect user privacy and data security.
Connection requirements: Support sufficient system capacity and support data reading from a large number of terminals.

2.2 Logistics and Warehousing

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

In logistics and warehousing application scenarios, a large number of packaging / goods need to be transferred, stored, loaded, unloaded and inventoried frequently at logistics stations or warehouses (tens of thousands of square meters). With the occurrence of warehouse ordering, goods warehousing, goods management and goods outbound, there will be a lot of storage information, which generally has the characteristics of frequent data operation and large amount of data.

In order to carry out digital information management of logistics packages/goods and improve the management efficiency of logistics and warehousing, a terminal can be attached on the surface of the packages/goods for acquisition of logistics information and management of the entire logistics process. Therefore, small terminal size is more conducive to industry applications. At the same time, due to the huge number of goods and when economic cost is taken into considerations, express delivery or warehouse suppliers can only accept extremely low-cost terminals.

Zero-power terminal has the characteristics of extremely low cost, small size, maintenance-free, durable, and long life cycle. In logistics and warehousing, the use of zero-power terminal to record, save, and update goods information, and build a logistics and warehousing system based on the zero-power communication can further reduce operating costs and significantly improve the efficiency of logistics and warehousing management. It also contributes to the realization of smart logistics and smart warehousing.

Figure 2.2-1 Zero-power tags in smart logistics and smart warehousing

- Specifically, zero-power technology can realize smart warehouse management and improve warehouse efficiency and productivity through the following:

Support Batch reading

A larger number of zero-power tags are read at the same time. When the goods arrive at the warehouse, the wireless tags attached to the goods can be read in batches (for example, read thousands of tags per second) to accurately obtain goods information, such as size/weight, manufacturer, expiration date, serial number, production line, etc., which can help to improve the efficiency and accuracy of logistics storage.

Support Large coverage

With zero-power communication, a wider range of reading and writing can be supported [3]. In the warehouse, one or a few network equipment are deployed to cover the whole warehouse. The wireless tag attached to the goods or containers will save its basic information and location information. Through the center network nodes set up in the warehouse, it can identify all the goods in the warehouse timely and quickly and help to take inventory quickly. It is convenient for managers to understand the distribution and total amount of inventory in time and realize the rapid prediction of storage demand.

Support Mobility management

Tags can be used to track location information [4]. When the goods move in the warehouse, the network equipment can identify and update the tag information in time. When it is necessary to pick and choose the corresponding goods, the tag can be read in the whole warehouse and it can quickly locate the goods and greatly improve the picking efficiency of the goods.

Figure 2.2-2 Application of Zero-power technology in Smart Warehousing

- Typical requirements for smart logistics and smart warehousing scenario are as follows:

Terminal requirements:

The zero-power terminal is in the form of a simple electronic tag. Since it is generally a large-scale application (each good will have a tag), the cost, size and power consumption of the tag need to be taken into account.

Tag size: extremely small size, convenient for large-scale application.
Tag cost: due to the huge number of goods in logistics and storage, extremely low cost is required.
Tag power consumption: the terminal power consumption is less than 1mw, battery free and maintenance free.
Communication distance:support communication in the range of tens of meters to hundreds of meters.

Network requirements:

Flexible deployment based on cellular network: Network equipment can be deployed in outdoor pole stations, indoor with DIS station spacing deployment, to provide basic coverage.
Coverage requirements: coverage distance requirements of a single station (indoor >30m, outdoor >100m).
Network security: authorization-based tag reading to protect privacy and data security.
Reading efficiency: large quantities of goods require simultaneous detection of a large number of tags (e.g., thousands per second).

2.3 Smart Home

Smart home takes housing as the platform and connects various devices at home through the Internet of things to build an efficient and livable system. Smart home makes use of various functions and means such as automatic control, lighting control, temperature control, anti-theft and alarm control of home appliances to make the home environment safer, more convenient and more comfortable. Sensors and small devices in smart homes scenario can communicate using backscattering technology [5].

Zero-power communication can achieve battery-free, which can greatly increase the service time of corresponding devices at smart homes and reduce maintenance costs. At the same time, due to its ultra-low cost, extremely small size, washable, flexible/foldable shape factors, it can be deployed flexibly at smart homes, such as embedded in walls, ceilings and furniture, or attached to keys, passports, clothes and shoes. Zero-power communication can expand the application of smart home scenarios and is extremely attractive to the smart home field.

Figure 2.3-1 Application of Zero-power technology in Smart Home

- Typical use cases for Smart Home scenario are as follows:

Item search

An extremely small, washable, flexible, foldable zero-power terminal can be attached to some items which are easily lost in the house, such as keys, passports, bank cards, wallets and others. When you need to find these items, you can quickly locate and find the lost items with the help of zero-power communication.

Environmental monitoring and alarm

Zero-power terminals are integrated with sensors to monitor the temperature, humidity, etc. of the house, and can also be used for warning in case of emergency such as gas leakage. The battery free feature of zero-power terminal can greatly increase the service time of the equipment and realize maintenance free.

Intelligent control

Zero-power terminals are integrated with sensors, which can realize intelligent control of home devices. For example, it can be used to control the switch of washing machines, air conditioners, televisions, curtains, etc. Home robots can also be navigated and provided more sophisticated control by tags embedded/attached to doors and furniture [6].

- Typical requirements for Smart Home scenario are as follows:

Terminal requirements:

The zero-power terminal is in the form of an electronic tag, which can be integrated with memory for data access or sensors for sensor information collection. In home applications, its cost, power consumption, size, waterproofing and foldability all need to be considered.

Tag size: extremely small size, convenient for large-scale application.
Tag type: Paper tag and anti-metal tag, support cleaning, with flexible and foldable shape.
Tag power consumption: Battery free, not involve battery replacement and other related maintenance issues.
Communication distance: Support communication in the range of tens of meters to hundreds of meters (Indoor).
Number of connections: Support tens to hundreds of device connections.
Communication delay: Adjustment of intelligent household appliances: 10ms to 100ms. Home positioning: 100 milliseconds to second level.

Network requirements:

Flexible deployment: Use smart terminals (smart phone or CPE) as gateway devices, or directly connect to base stations.
Coverage requirements: coverage distance requirements of a single station (Indoor 10-30m (connected to smart devices). Outdoor >100m (directly connected to base station).
Network security: authorization-based tag reading to protect privacy and data security.
Large connection: There are a large number of indoor zero-power terminals, ranging from tens to hundreds.
Energy harvesting signal: The signal of smart devices (e.g., smart phones, CPE and WIFI) in the home can be used as wireless power sourcing signal for the zero-power terminal.

2.4 Smart Wearable

It is user-centered in the smart wearable scenario and various devices worn by consumers are connected through the Internet of things technology, which has been applied in many fields (such as health monitoring [7], activity recognition [8][9], assisted living [10], mobile perception [11], smart clothing [12], indoor positioning [13], etc.). At present, the mainstream product forms include form factors related to watches (including watches and wristbands), form factors related to shoes (including shoes, socks or other products to be worn on legs), form factors related to Glass (including glasses, helmets, headband, etc.). In addition, it also includes various non-mainstream product forms such as smart clothes, schoolbags, crutches and accessories.

Smart wearable devices driven by batteries have a relatively short battery life. If more functions are enabled, the power consumption will further increase, and users often need to charge frequently to ensure the normal use of the device. This will greatly affect the user experience.

Zero-power terminal has excellent characteristics such as extremely low cost, extremely small size, extremely low power consumption (battery-free), flexible/foldable, and even washable. It is particularly suitable for smart wearable scenarios and easy to be accepted by consumer-related industries (such as kindergartens, garment factories, etc.). On the one hand, zero-power terminals can obtain energy through energy harvesting, which will fundamentally solve the problem that smart wearable devices need to be charged frequently. On the other hand, the zero-power terminal has the advantages of low cost, small size, soft material, washable and foldable, which greatly improves the comfort of wearing and makes the user experience better.

Figure 2.4-1 Application of Zero-power technology in Wearable field

- Typical use cases for smart wearable are as follows:

Health monitoring

Zero-power terminal is integrated with sensors, embedded in wristbands [14], shoes, socks and other wearable products for health monitoring and timely feedback on people's physical condition. Sleep status, weight information, heart rate, blood pressure and other data are monitored and collected via the terminal.

Positioning and tracking

Zero-power terminal can support positioning [15], and it can be used for positioning and tracking of the elderly, children or hospital patients when they get lost. More comfortable materials can optimize the wearing experience, and the zero-power feature can greatly increase the service time.

Portable payment

Bound with personal information, zero-power terminal can be used for portable payment such as bus, subway, shopping etc.

- Typical requirements for Smart Home scenario are as follows:

Terminal requirements:	The zero-power terminal is in the form of an electronic tag, which can be integrated with memory for data access or integrated with sensors for sensor information collection. For the sake of wearing convenience, it should have a small size, battery free, waterproof, flexible and foldable shape. **Tag size:** Extremely small size, convenient to wear. **Tag type:** Paper tag and anti-metal tag, support cleaning, with flexible and foldable shape. **Tag power consumption:** Battery free, not involve battery replacement and other related maintenance issues. **Communication distance:** Support communications within a range of tens of meters (e.g., 30~50m). When a smart terminal is used as a relay, the communication distance can be 1m to 2m. **Number of connections:** Support tens to hundreds of device connections. **Service continuity requirements:** Meet the periodic transmission requirements, and the period of service traffic ranges from seconds to minutes.

Network requirements:	**Flexible deployment:** For wearable scenarios, since users carry both wearable devices and traditional smart terminals in most scenarios, smart terminals can serve as relay devices or gateway devices to collect and transmit data collected by wearable devices. Or wearable devices can directly connect to base stations. **Network security:** authorization-based tag reading to protect privacy and data security. **Energy harvesting signal:** The signal of smart terminal can be used as wireless power sourcing signal for the zero-power terminal.

2.5 Medical Health

The medical health field involves patient information management, health data monitoring and management, medical emergency management, drug storage, blood information management, drug preparation error prevention, medical devices and drug traceability, information sharing and interconnection, etc. In the process of medical treatment, it is necessary to ensure that the patient uses the correct medicine, the correct dosage, and the correct medication method at the correct time. At the same time, the clinical medical process requires high-quality monitoring and management throughout the entire process.

Zero-power terminal has excellent characteristics such as extremely low cost, extremely small size, extremely low power consumption (battery-free), flexible foldable, washable, etc. It can help hospitals to realize intelligent medical treatment and intelligent management of things, and support the digital collection, processing, storage, transmission and sharing of medical information, equipment information, drug information, personnel information and management information within the hospital. In addition, the excellent characteristics of zero-power technology make it possible to perform in-body communication and treatment. There are already some related researches on in-body communication based on backscattering in the industry [16][17].

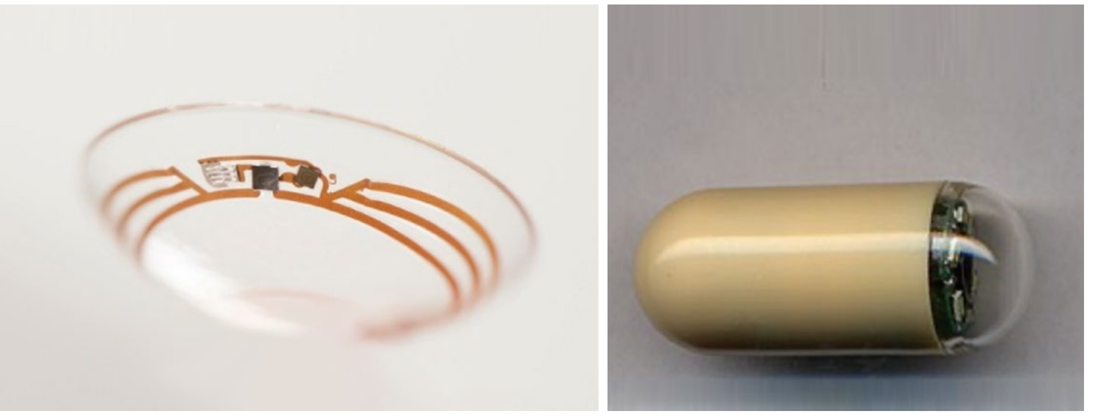

Figure 2.5-1 Application of Zero-power technology in Medical Health

- Typical use cases for Medical Health are as follows:

Special instrument monitoring

Zero-power terminal has the characteristics of extremely small size and extremely low power consumption (battery-free), which can assist the monitoring of special devices. For example, some devices implanted in the human body can use the zero-power terminal to monitor important parameters, ensure the normal operation of the relevant equipment and replace the faulty equipment timely. Because it is to monitor the equipment in the human body, the zero-power terminal without battery can be maintenance-free, with a very long service life.

Subcutaneous / in-body health data collection

Zero-power terminal integrated with sensors can be used for health data collection. For example, Google Contact Lens [18] collects radio frequency energy through wireless controller, and backscatters the measured blood sugar level to the wireless controller for diagnosis, so as to avoid the pain of blood test for diabetic patients. Due to its good features such as battery-free, waterproof and extremely small size, zero-power terminal can even be implanted into the human body for in-body health data collection. For example, capsule endoscopy [19] can be used to record internal images of the gastrointestinal tract through the combination of a zero-power terminal and a sensor for medical diagnosis, it is also able to take biopsies and release medication at specific locations of the entire gastrointestinal tract. While realizing more detailed examination, it can also avoid the pain of patients undergoing gastroscopy.

Patient data collection and verification

A very small zero-power terminal can be embedded in a wristband or clothing for data collection and verification. In the process of patient diagnosis, taking medicine and treatment, data can be collected without disturbing patients, so as to realize efficient medical treatment management. It can also help to ensure that patients take the appropriate dose of drugs at the appropriate time, verify whether the name and specifications of infusion and injection drugs are correct, whether treatment items is completed, and whether there will be adverse reactions, etc.

Management of drugs and medical devices

The zero-power terminal is very small and can be attached to the bottle of equipment and medicine for the management and tracking of drugs and medical devices. Large medical centers generally have a large number of critical medical assets and storage bases for medical items, and logistics personnel have to find the required items from tens of thousands of items according to orders every day. The packaging of these medical items is highly similar while the use is totally different. Therefore, the hospital logistics department often has to spend huge manpower to find and check these items. In addition, the misplacement of medical items is likely to occur in the process of warehouse adjustment, resulting in large-scale damage or drug accidents after circulation to the market. By using the zero-power terminal, management can be facilitated, and the management efficiency, the reliability of medicines and medical devices can be improved.

- Typical requirements for Medical Health are as follows:

Terminal requirements:	The zero-power terminal is in the form of an electronic tag, which can also be integrated with sensors. **Tag size:** Extremely small size. **Tag type:** Paper tag and anti-metal tag, support cleaning, with flexible and foldable shape. **Tag power consumption:** Battery free, not involve battery replacement and other related maintenance issues. **Communication distance:**Support communication in the range of tens of meters to hundreds of meters. **Number of connections:**Support tens to hundreds of device connections. **Communication delay:** 100 milliseconds to second.
Network requirements:	**Flexible deployment:**Network equipment can be deployed in outdoor pole stations, indoor with DIS (Digital Indoor System) station spacing deployment, to provide basic coverage. **Coverage requirements:** coverage distance requirements of a single station (indoor >30m, outdoor >100m). **Network security:** authorization-based tag reading to protect privacy and data security.

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TECHNICAL PRINCIPLES OF ZERO-POWER COMMUNICATION

Zero-power Communication mainly utilizes RF power harvesting, backscattering, and low-power computing technology to implement battery-less terminal. As shown in Figure 3-1, the terminal obtains the energy to drive itself through energy harvesting. It uses low-power computing and backscattering for data transmission.

RF power harvesting aims to convert radio frequency energy into direct current (RF-DC). The energy can be stored in an unit such as a capacitor or it can be directly used to drive sensors, logic circuits and digital chips. It enables the device to execute operations such as computation, modulation of backscatter signal, and collection and processing of sensor information.

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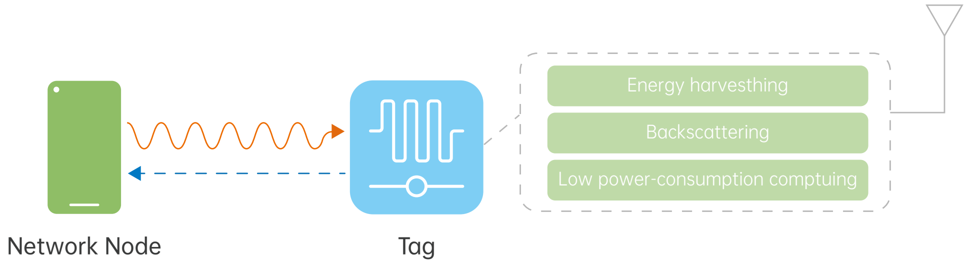

Figure 3-1 Zero-power communication system

In zero-power communication system, the backscattering transmitter modulates and reflects the received RF signal to transmit data instead of generating the RF signal itself. This technology has been widely used in practical production, such as radio frequency identification (RFID), tracking equipment, remote switches, medical telemetry, and low-cost sensor networks.

3.1 RF power harvesting

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 zero-power communication, the collected energy is used to drive the load circuit (low-power computing, sensors, etc.) to achieve battery-less communication.

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 show 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 -30 dBm it is very challenging to effectively collect RF energy and rectify it into a usable DC voltage.

Generally, the power required to drive an ultra-low power circuit is at least 10uw. In order to meet requirements of the low-power consumption and backscattering communication, it can be seen that improving the efficiency of energy collection and conversion under the condition of ultra-low input power is one of the most important challenges in the research and development of zero-power communication system [2].

Table 3.1-1 Input power vs. RF energy conversion efficiency [2]

Efficiency(%)	Input power (dBm)	Center frequency (MHz)	RF power Harvestor
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 COMS 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).

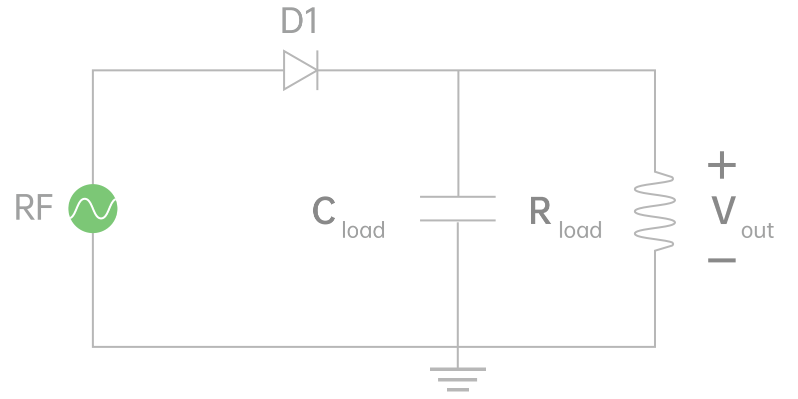

Figure 3.1-1 Half-wave rectifier

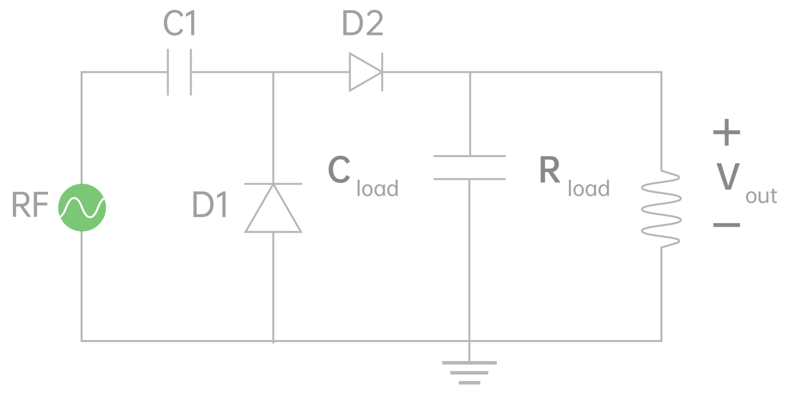

Figure 3.1-2 Single stage voltage multiplier

3.2 Backscattering

The backscattering 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), and the tag achieves signal modulation by changing its RCS. The backscattering transmitter modulates the reflected RF signal to transmit data without generating the RF signal itself.

Backscattering was first proposed by Stockman in 1948 [4]. However, traditional backscattering communication cannot be widely used in data-intensive wireless communication systems due to the following limitations.

1) The activation of backscatter transmitters relies on an external power supply such as an active interrogator (also called a reader or carrier emitter) which is costly and bulky.

2) A backscatter transmitter passively responds only when inquired by a reader. The communication link is restricted in one hop, typically with the distance ranging from a few centimeters to a few meters.

3) A backscatter transmitter' s reflected signal could be severely impaired by adjacent active readers, significantly limiting the device usage in a dense deployment scenario.

Recently, Ambient Backscatter Communication (AmBC) has emerged to overcome some of the above limitations. The system generally includes three parts: ambient radio-frequency (RF) source, backscatter device, and reader. In an ambient backscatter communication system, backscatter devices can communicate with each other by using signals broadcast from ambient RF sources such as TV towers, FM towers, cellular base stations, and Wi-Fi access points (APs). Further, by separating the carrier transmitter and the backscatter receiver, the number of RF components of the backscatter device is minimized, and the device can be actively operated when it collects enough energy from RF source without activating receiver.

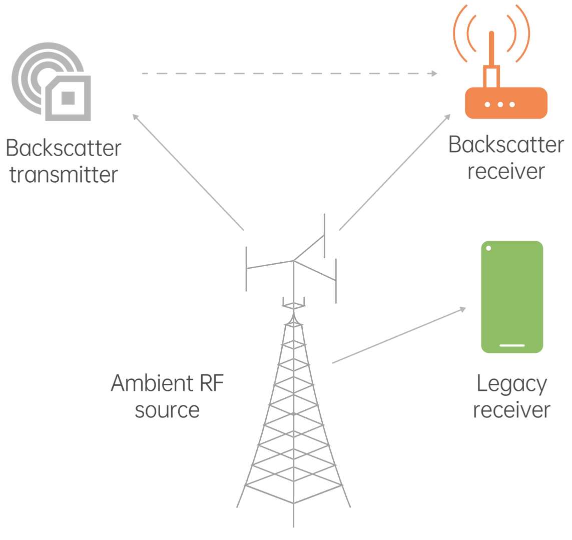

Figure 3.2-1 Illustration of AmBC system [6]

Zero-power devices (such as backscatter tags) receive the carrier signal sent by the reader, collect energy through the RF power harvesting module. After obtaining energy, the backscatter tag drives the corresponding circuit to modulate the incoming carrier wave and perform backscattering communication.

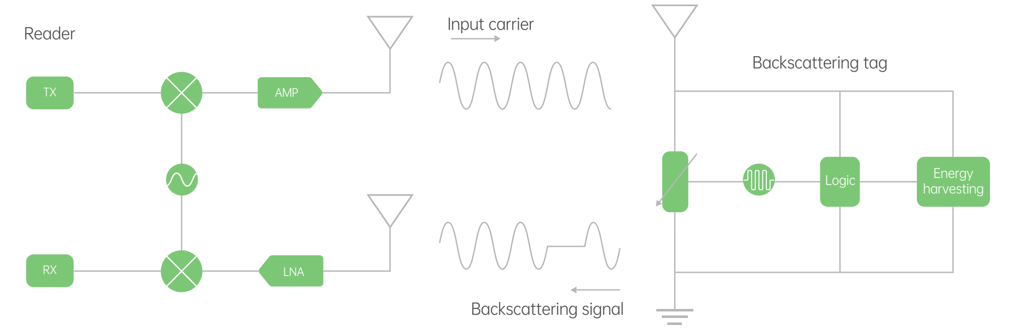

Figure 3.2-2 Backscattering communication

In a backscattering communication system, load modulation is usually used. The load modulation technology mainly includes two methods: resistance-based load modulation and capacitor-based load modulation. For resistance-based load modulation, a resistor which is called a load modulation resistor, is connected in parallel to the load. The resistor is turned on or turned off according to the clock of the data stream, and the switch is controlled by the binary data encoding. For capacitor-based load modulation, a capacitor is connected in parallel with the load to replace the load modulation resistor.

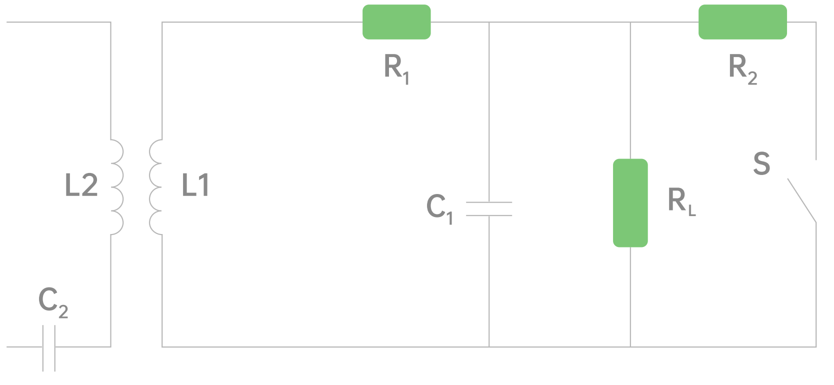

Figure 3.2-3 Resistance-based modulation

Taking resistance-based modulation which can achieve 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 which indicates a bit '1'.

As shown in Figure 3.2-4, the terminal can realize 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.

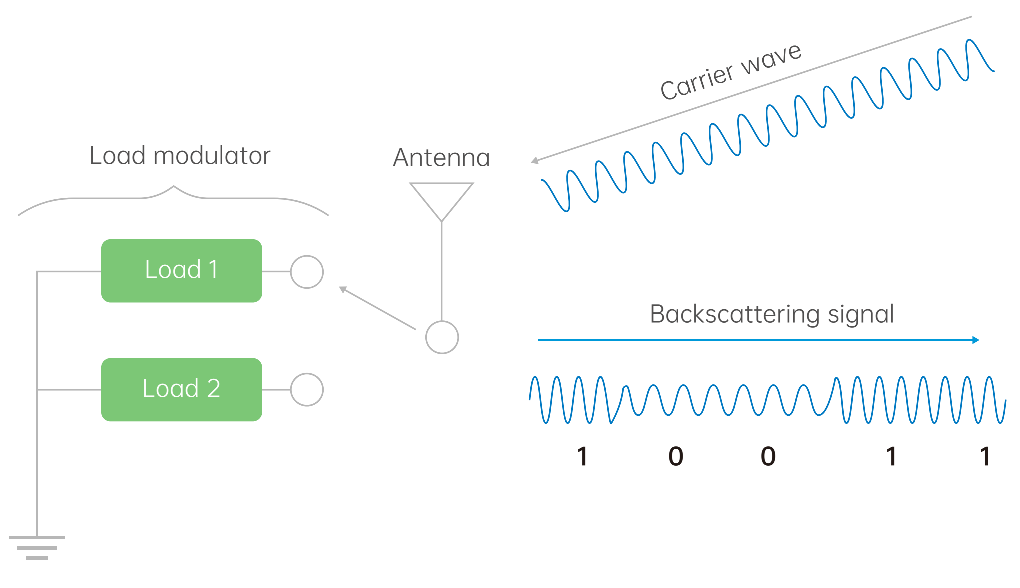

Figure 3.2-4 ASK modulation [1]

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

Therefore, backscattering communication achieves extremely low-complexity signal modulation and transmission via impedance modulation. The backscatter terminal does not require complex RF structures, such as PA, high-precision oscillator, duplexer, and high-precision filter. There is also no need for complex baseband processing, complex channel estimation and equalization operations. Therefore, it makes zero-power communication possible with back-scattering technology.

3.3 Low-power computing

The main characteristics of zero-power communication is to realize backscattering 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 is greatly improved, complex computation using very limited energy remains challenging.

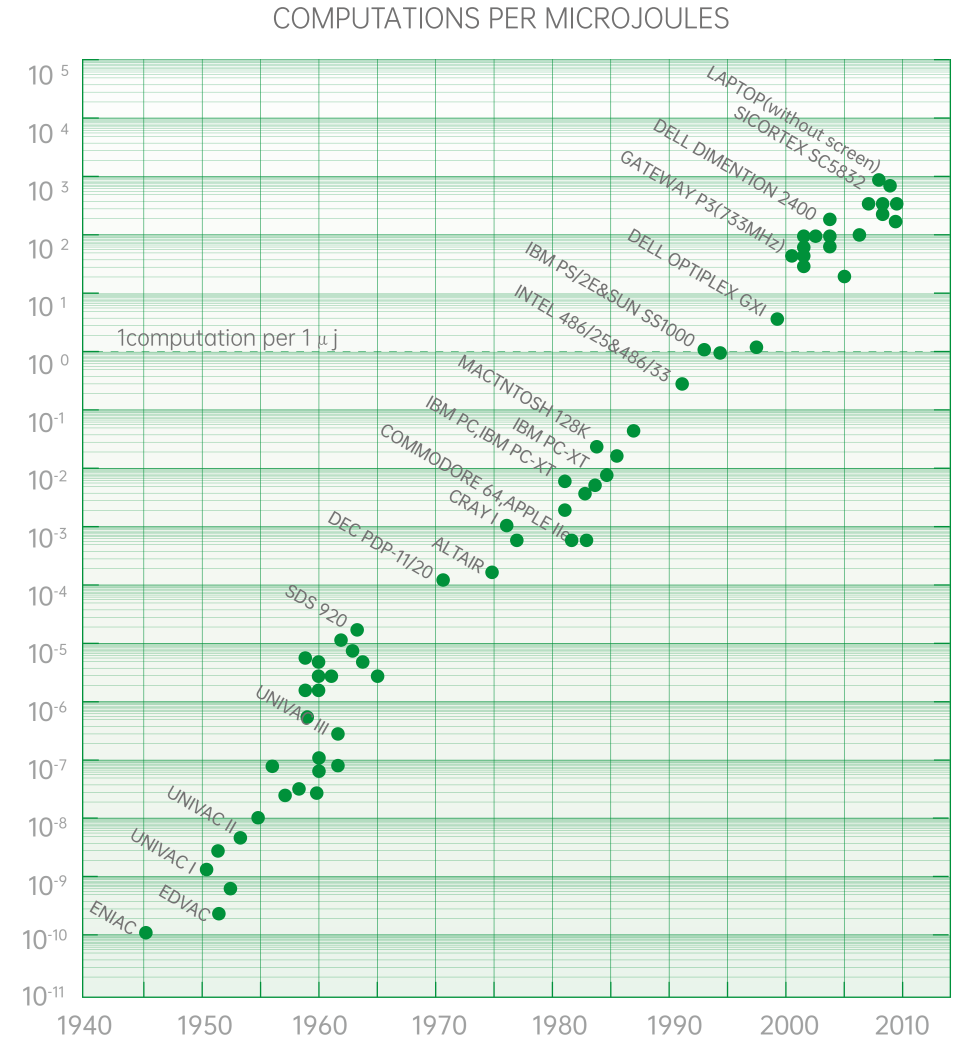

Figure 3.3-1 Computation develops with low power consumption [7]

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

Low power-consumption receiver

To reduce complexity and power consumption of zero-power devices, it can be considered to support only broadcast transmission without a receiver or support a simple receiver by using a comparator to implement simple ASK modulation and demodulation.

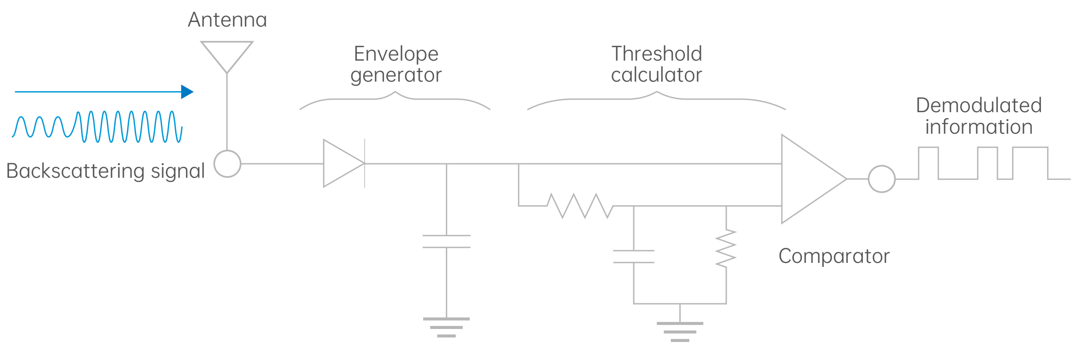

Figure 3.3-2 Illustration of envelope detector

Low power-consumption chip

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

Simple coding and modulation

ASK and FSK can be used as the basic modulation schemes for backscattering. 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 zero-power system.

3.4 References

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OVERALL DESIGN OF ZERO-POWER COMMUNICATION SYSTEM

For different application scenarios, zero power communication can use different frequency bands. Different network deployment can be utilized for different communication requirements. It should also be considered for coexistence with existing communication systems.

04

4.1 Frequency band and link budget of zero-power communication

In the deployment of zero-power communication, its communication frequency band should be appropriately considered. In general, zero-power communication can use both unlicensed and licensed frequency bands. For operation in unlicensed frequency bands, the spectrum resources can be used freely and flexibly as long as it meets the specification requirements. It can reduce operating costs and expand the application of zero-power communication system. In contrary to unlicensed band operation, using the licensed frequency band can make full use of the spectrum resources of existing operators. Moreover, the maximum transmission power on the licensed frequency band is relatively high, which further ease to achieve wide coverage. Furthermore, operators can avoid interference between non-zero-power system and zero-power system by reasonably planning the frequency resource utilization, which is conducive to building a reliable zero-power communication network. Therefore, when designing zero-power communication network, both unlicensed frequency band and licensed frequency band need to be considered.

Similar as in traditional communication network, the coverage of a zero-power communication network is limited by multiple factors, e.g., the transmission power of network equipment, working frequency band, equipment antenna gain, equipment receiver sensitivity, etc. In addition, the coverage of zero-power communication network is closely related to the power level of wireless power harvesting signals.

For the forward link i.e., from the network node to the terminal, considering about serval to ten microwatts are needed to drive the low-power consumption circuit, the received signal shall have a signal strength above -20 dBm, i.e. equivalent to ten microwatts. This is way higher than the receiver sensitivity of a traditional terminal (about -100dBm). If a zero-power terminal has a certain energy storage capacity, e.g. equipped with an energy storage capacitor, the signal strength of the received RF signal at the terminal can be relaxed to -30dBm. In this case, the terminal can reserve the energy used in the operation through a long period of energy harvesting. However, the transmission power of the network node is restricted by regional regulation, 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 terminal to the network node. The signal strength of the backscattered signal apart from the antenna of the terminal 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 [1] 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 zero-power communication network 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 targeted, and 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 IWSN scenario, and the whole logistics station or warehouse shall be covered for smart logistics and smart warehousing case. 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 zero-power communication networks that meet the requirements of the vertical industry. In addition, the lower the frequency, the easier to improve the coverage of zero-power consumption communication network (as shown in table 4.1-1).

The antenna gain of the terminal also affects the coverage of the zero-power communication network, and 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 zero-power terminals. In order to achieve extended coverage, zero-power terminals 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 is equipped with the conventional batteries, the downlink coverage of the zero-power terminal 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 zero-power terminal. Based on the current research, the sensitivity of zero-power terminal downlink receiver can reach -50/-60dBm or even lower.

A preliminary estimation of the link budget is given in Table 4.1-1. Considering the operational frequency band, transmission power, transmission loss, network equipment antenna gain, zero-power terminal antenna gain, backscattering coefficient (the ratio of the signal strength of terminal reflection signal and power supply signal) and other factors, the zero-power communication is preliminarily evaluated as shown in the following table (calculated by Friis equation,):

Table 4.1-1 Estimation of link budget

System configuration	Case1	Case2	Case3	Case4	Case5	Case6	Case7
Carrier frequency (GHz)	2.4	0.7	0.7	0.7	0.7	0.7	0.7
Network node							
(1) Tx power (dBm)	36	36	36	36	36	36	36
(2) Antenna gain (dBi)	8	8	8	8	8	8	8
(3) Receiver sensitivity (dBm)	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00
(4) Maximum backward link communication distance (m)*	176.89	606.48	191.78	1917.84	606.48	60.65	606.48
Zero-power terminal							
(5) Antenna gain (dBi)	2	2	2	12	12	2	2
(6) Receiver sensitivity (dBm)	-20	-20	-30	-20	-30	-40	-40
(7) Maximum forward link communication distance (m)	19.85	68.05	215.19	215.19	680.48	680.48	680.48
(8) Backscatter transmission loss (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0
(9) Low Noise Amplifier factor (dB)	0.0	0.0	0.0	0.0	0.0	0.0	20.0

Note*: Maximum backward link communication distance in (4) is the value when the signal strength received by the zero-power terminal just meets the RF sensitivity

● Based on the analysis of Table 4.1- 1, the following conclusions can be drawn:

1) When the working frequency band of zero-power communication is 700MHz, under the basic assumption, that is, the downlink signal transmission power of network nodes is 36dBm, the antenna gain of network nodes is 8dBi, the receiver sensitivity of zero-power terminal is -20dBm (requirement of the RF power sourcing signal), and the antenna gain of zero-power terminal is 2dBi. Through the calculation, the maximum communication distance of the forward link (that is, the maximum distance to drive the zero-power terminal by collecting the energy of the downlink signal of the network node) is 68m (as shown in case2).

2) When other conditions are the same, the coverage can be increased by using a lower frequency band. As shown in case 1 and case 2, using the frequency band of 2.4GHz, the maximum forward link communication distance is 20m andthe maximum backward link communication distance is 176m. However, when 700MHz frequency band is used, the maximum forward link communication distance increases to 68m and the maximum backward link communication distance increases to 606 m.

3) The maximum forward link communication distance can be increased by using the energy storage unit to reduce the threshold of the received signal strength required by the zero-power. As shown in case 2 and case 3, when the frequency band, network node antenna transmission power, antenna gain and other conditions are consistent, the receiver sensitivity of the zero-power terminal with energy storage unit is -30dBm. In this case, the maximum forward link communication distance can be increased from 68m to 215m, which is expanded by about three times.

4) The use of high-gain antennas can effectively improve the coverage of the forward link. As shown in case 3 and case 5, using a higher gain receiving antenna (receiving antenna gain of case 5 is 12dBi), the maximum forward link communication distance can be increased from 215m to 680m, which is expanded by about three times.

5) With the further improvement of the receiver sensitivity of zero-power terminal, the coverage of the forward link can be improved, but the communication distance of the backward link (the uplink link that is from the zero-power terminal to the network node) gradually decreases. As shown in case2 and case6, when the receiver sensitivity decreases from -20dBm to -40dBm (In this case, the terminal can have a battery and the downlink communication distance is restricted by the DL receiver sensitivity instead of the signal strength of the RF power sourcing signal), the communication distance increases of forward link from 68m to 680m while the communication distance increases of backward link decreased from 606m to 60m. This is because the signal received by the zero-power terminal will be further decreased during the backscattering transmission, which results in the low signal strength of the uplink signal (i.e., the signal backscattered from the zero-power terminal to the network node).

6) The integration of LNA (low noise amplifier, LNA) in zero-power terminal with high sensitivity receiver can effectively make up the communication distance of backward link. Compared with case6, the maximum communication distance of backward link in case 7 can be increased from 60m to 600m by integrating an LNA.

4.2 Framework of zero-power communication

Zero-power communication systems can be constructed in a framework using cellular communication, sidelink communication, and hybrid of cellular communication and sidelink communication.

4.2.1 Cellular based zero-power communication

The cellular based zero-power communication system can support the large-scale deployment and centralized control of zero-power terminals. It aims to solve the problems of insufficient communication distance, high deployment cost and low system efficiency of traditional technologies (such as RFID) with point-to-point and point-to-multipoint communication requirements. Thanks to the advantages of cellular network in the aspects of cell coverage and resource utilization, the cellular based zero-power communication system can manage the zero-power terminals in the network in a wide range and centralized way, which can greatly improve the system efficiency and save the deployment cost. Therefore, the cellular based zero-power communication system is particularly suitable for some application scenarios. In the industrial sensor network scenario, the deployment environment of terminals may be harsh, the number of the terminals may be huge, and the deployment and maintenance cost of using traditional active terminals is high. Cellular based zero-power communication can remotely and centrally manage zero-power terminals for automatic control and information interaction. In logistics and warehousing scenarios, a large number of goods need to be identified, tracked and counted. Compared with the existing methods based on QR code or RFID, the cellular zero-power communication system can overcome the low efficiency and low reliability of the existing optical identification and short-range identification, greatly simplify the identification process, save the investment of manpower and equipment and reduce the cost. In the smart farming and animal husbandry scenario, livestock carrying zero-power terminals can be managed in the farm through cellular network, including statistics, positioning, tracking, etc. Other scenarios applicable to cellular based zero-power communication systems also include wearable, medical, transportation, etc.

● The cellular based zero-power communication system can include the following communication modes:

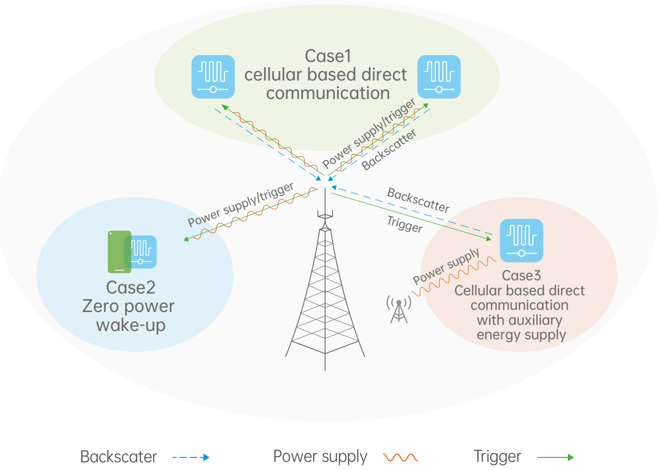

Figure 4.2-1 Cellular based zero-power communication system

Case 1: Cellular based direct communication

The base station communicates directly with the zero-power terminal. The base station provides wireless power sourcing signal and trigger signal to the zero-power terminal. The wireless power sourcing signal is used to provide energy to the zero-power terminal. The trigger signal can carry the control information . The zero-power terminal transmits the information to the base station via back-scattering.

Case 2:Zero-power wake-up

In view of the excellent characteristics of ultra-low power consumption, zero-power terminal can be combined with traditional terminals and undertake and complete some low-power operations, so as to realize the energy saving of traditional terminals. For example, a zero-power terminal can be used as wake-up receiver (WUR, Wake-Up Radio) for a traditional terminal. When the base station needs to communicate with the traditional terminal, it first sends a wake-up signal, and the zero-power terminal wakes up the traditional terminal when detecting the wake-up signal. For traditional terminals (especially IoT terminals that are in RRC idle/inactive states for most of the time), it can save the power consumption consumed for traditional paging monitoring, so as to achieve significant power saving.

Case 3: Cellular based direct communication with auxiliary energy supply

The zero-power terminal can obtain wireless power supply not only from the base station communicating with it, but also from the third-party equipment. The strength of the energy supply signal reaching the terminal needs to meet a certain threshold, such as - 20dBm or - 30dBm (when the terminal has energy storage unit), which results in that when the transmission power of the power supply signal is limited, the coverage of the power supply signal transmitted by the network equipment is small, generally in the range of tens of meters to 100 meters. From the perspective of cellular coverage, the coverage of wireless power supply is much smaller than that of communication signals. Therefore, the coverage of wireless power supply signal is the bottleneck. Wireless power supply via more network nodes can significantly improve the coverage, so as to improve the cell coverage of zero-power communication as much as possible. Therefore, other nodes in the network can be used for wireless power supply. Potential power supply nodes include smart phones, relay nodes, CPE, etc. If necessary, dedicated power supply nodes can also be deployed. The traditional wireless communication signals (such as synchronization signal, broadcast signal, data channel, etc.) sent by these nodes can be used to provide wireless power for zero-power terminals, or these power supply nodes can also send specific wireless power supply signals. Further, the base station and the zero-power terminal exchange information through downlink trigger information and uplink backscattering.

4.2.2 Sidelink based zero-power communication

The sidelink based zero-power communication can realize the sidelink communication between the zero-power terminal and other types of terminals (such as smart phones, CPE or other IoT terminal devices). The sidelink between terminals can perform direct communication without relying on the cellular network. Sidelink based zero-power communication also has a wide range of application scenarios, especially suitable for low-cost and short-range communication. For example, in the smart home scenario, the sidelink between the smart terminal and the zero-power terminal is directly connected, which can realize the functions of object search, home asset management, environmental monitoring, intelligent control and so on. In the smart wearable scenario, the sidelink based zero-power communication can also realize the information reading or intelligent control of the data of the zero-power wearable device.

- The sidelink based zero-power communication system can include the following communication modes:

Case 1: Sidelink based direct communication

The zero-power terminal communicates directly with an intelligent device. The intelligent device sends a wireless power supply signal and a trigger signal to the zero-power terminal. The zero-power terminal transmits the information to the intelligent device through backscattering to realize sidelink communication. The intelligent device can be a mobile phone or a control node (such as CPE), corresponding to case1-1 and case1-2 in the block diagram of sidelink based zero-power communication system in Figure 4.2-2.

Case 2: Sidelink based direct communication with auxiliary energy supply

In order to realize the sidelink based direct communication between the zero-power terminal and the intelligent device, the wireless power supply signal of the zero-power terminal cannot directly come from the intelligent device, but from the third-party device. As shown in case2 in Figure 4.2-2, the wireless power supply signal required for the sidelink between the zero-power terminal and the mobile phone comes from the control node. The zero-power terminal receives the trigger signal sent by the intelligent device and transmits the information to the intelligent device via backscattering.

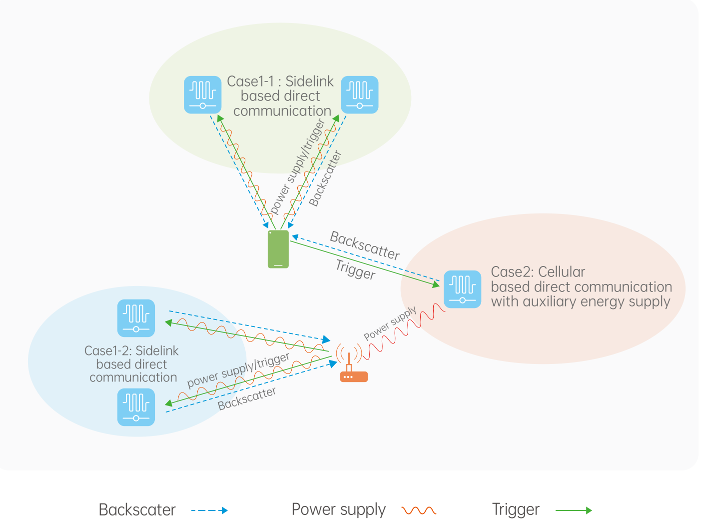

Figure 4.2-2 Sidelink based zero-power communication system

4.2.3 Hybrid of cellular and sidelink based zero-power communication system

In the actual deployment of the zero-power communication system, the above cellular and sidelink based zero-power communication system can also be flexibly coexisted or combined, so as to allow more potential application scenarios. The system block diagram of the hybrid of cellular and sidelink based zero-power communication system is as follows. It can include a variety of communication modes, for example, as shown in Figure 4.2-3:

Case1: Zero-power communication with UE assisted power supply/trigger

The zero-power terminal is powered and triggered by the intelligent terminal in the network, and the backscatter signal of the zero-power terminal is received by the base station. The power supply and trigger operation of the intelligent terminal can be controlled by the base station through air interface signaling.

Case2: Sidelink based zero-power communication with network power supply/trigger

The base station provides wireless power supply and trigger signaling to the zero-power terminal. The backscatter signal of the zero-power terminal is received by the intelligent terminal to complete sidelink communication. Further, the intelligent terminal sends data to the base station.

Case3: Zero-power communication with UE assisted energy supply

The base station provides wireless power supply and trigger signaling to the zero-power terminal. The backscatter signal of the zero-power terminal is received by the intelligent terminal to complete sidelink communication. Further, the intelligent terminal sends data to the base station. The intelligent terminal in the network provides auxiliary energy for the zero-power terminal. The base station sends trigger information to the zero-power terminal and receives the backscatter signal of the zero-power terminal. The intelligent terminal provides auxiliary energy supply for zero-power terminal, which can be controlled by the base station through air interface signaling.

Case4: Network controlled sidelink based zero-power communication

The intelligent terminal receives the air interface signaling and data of the network. The intelligent terminal supplies energy and triggers for the zero-power terminal, receives the backscatter signal of the zero-power terminal, and completes the sidelink communication.

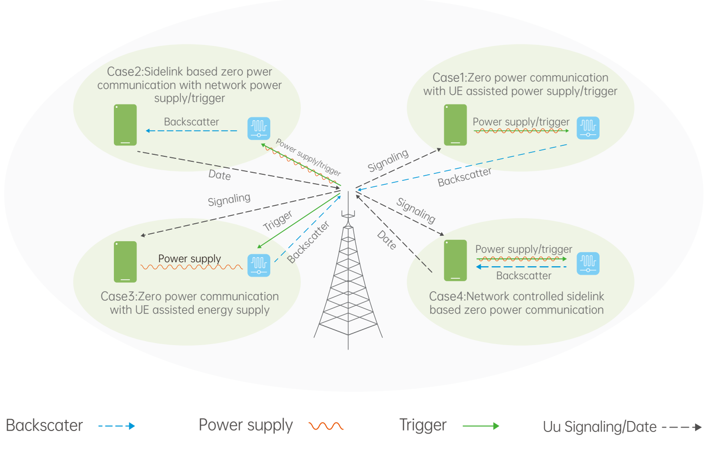

Figure 4.2-3 Hybrid of cellular and sidelink based zero-power communication system

It can be seen from the discussion in this section that different zero-power communication modes can be considered based on actual requirements in different application scenarios. We need to further study the characteristics of various deployment scenarios and communication modes, so as to give full play to the application potential of zero-power communication system.

4.3 Coexistence of zero-power IoT and 4G/5G systems

Since the sensitivity of the receiver of the traditional 4G/5G terminal is much lower than that of the zero-power terminal, it is also necessary to study the coexistence and interference issues of the zero-power communication system and the existing 4G/5G network.

From the perspective of frequency deployment there are three modes of coexistence for NB-IoT/eMTC and NR that include in-band deployment, guard-band deployment and standalone deployment. Similarly, these three modes can also be considered for coexistence of zero-power communication systems and existing 4G/5G systems.

For the coexistence of zero-power communication systems and existing 4G/5G 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.

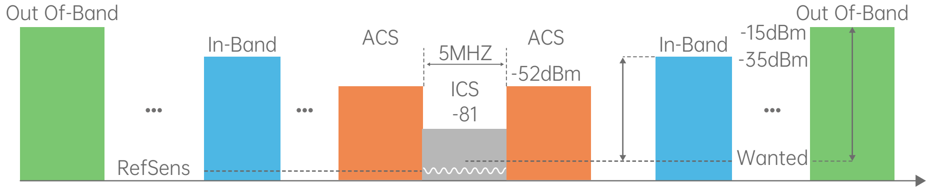

Figure 4.3-1 Rx requirements for coexistence

No matter whether a zero-power device is deployed with in-band mode, guard band mode or standalone mode, the received signal or reflected signal of the zero-power device may fall into the adjacent band or in-band of the 4G/5G terminal, forming adjacent-band interference or blocking, as shown in figure 4.3-2. In this case, the interference signal should meet RF Rx requirements of the 4G/5G terminal's receiver. Otherwise, it will cause the receiver performance degradation, e.g., maximum receiver sensitivity reeducation (MSD).

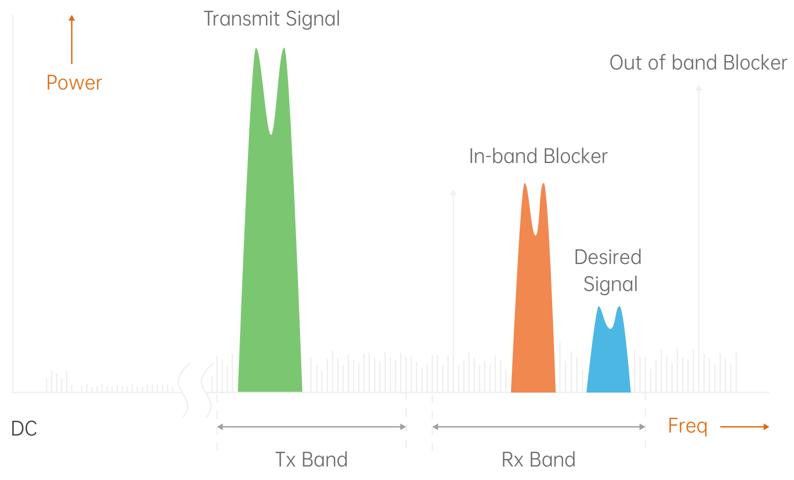

Figure 4.3-2 Receiver blocking

In particular, for in-band mode, it is necessary to avoid co-channel interference between systems. Whether the transmitted signal and backscattered signal would interfere 4G/5G terminals on the same band needs to be studied. For example, the network needs to send a strong signal so that the received signal strength by the zero-power terminal is above -20dBm. Such a strong signal may affect the performance of existing terminals considering the maximum input power requirement of -15dBm for 4G/5G UE.

For in-device coexistence, it will be more complicated, since additional interference including possible harmonics and intermodulation also need to be considered. In addition, the coexistence with WiFi, Bluetooth, Beidou, GPS also need to be analyzed based on the actual operating band.

On the contrary, for stand-alone deployment mode, the coexistence will be much simpler for zero-power device.

4.4 References

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KEY TECHNIQUES AND THE CHALLENGES OF ZERO-POWER COMMUNICATION

Zero-power communication terminals rely on the energy obtained externally. In order to support zero-power communication, network equipment first needs to provide wireless power supply function. In Section 5.1, we will analyze the requirements and challenges of wireless power supply when supporting zero-power communication. Further, in order to adapt to the minimalist hardware structure and extremely low complexity of zero-power terminal, we will analyze the challenges of data transmission of zero-power terminal 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 terminal also requires lightweight protocol stack and lightweight security mechanism, which will be described in section 5.3 and section 5.4 respectively. Finally, zero-power communication also puts forward new requirements for network architecture. We will discuss the simplified network architecture suitable for zero-power communication in section 5.5.

05

5.1 The requirements and challenges of wireless power sourcing

As described in Section 3.1, the zero-power terminal itself does not need to carry a battery inside, so before communication, the terminal needs to harvest wireless power supply signals to obtain the energy needed. In order to support the zero-power terminal to communicate in the 5G network, it needs to provide wireless power supply to the zero-power terminal. Compared with the traditional communication system, how to effectively supply energy to the zero-power terminal in a reasonable way so as to provide appropriate network coverage is a new challenge for zero-power communication system.

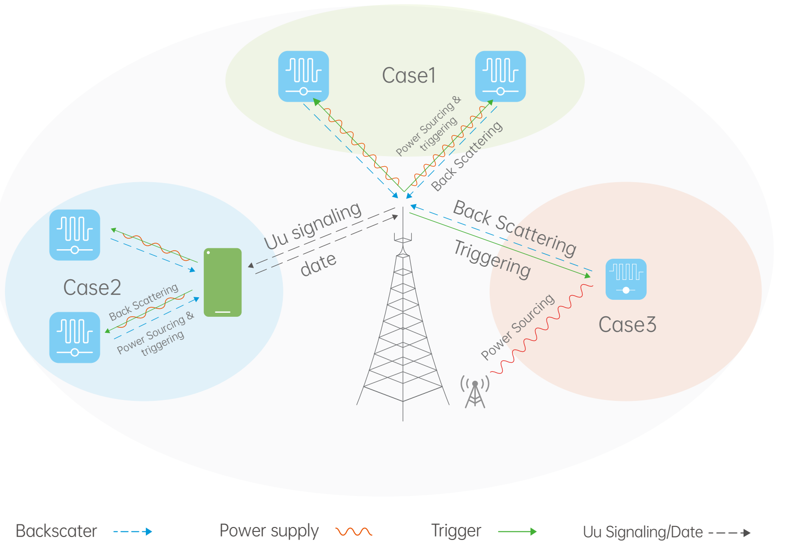

Figure 5.1-1 Various schemes for wireless power supply

Fortunately, there are plenty of network nodes in 5G network such as base station equipment, user terminal equipment, relay equipment, etc. All these network nodes have the function of transmitting wireless signals. Therefore, these devices can be used to provide wireless power to zero-power consumption terminals.

As shown in Figure 5.1-1, when zero-power terminal is deployed in the cellular network, the base station can directly send wireless power supply signal to the terminal, as shown in case 1 in the Figure. In this case, each time before the base station communicates with the terminal, it needs to send a wireless power supply signal to the terminal to make it obtain sufficient energy to be activated. In the communication process, the wireless power supply signal also needs to be continuously transmitted to enable the terminal to obtain the energy required to maintain normal operation. For example, in the process of downlink communication, the terminal needs to receive the wireless power supply signal to obtain the energy needed to maintain the terminal 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 terminal sends data to the network equipment, it is also necessary to continuously send the wireless power supply signal to the terminal. At this time, the wireless power supply signal provides the energy required by the terminal for data acquisition (such as reading data from the sensor or memory), coding and other operations. In addition, the wireless power supply signal is also used as the carrier signal for backscattering.

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 terminals, when the wireless power supply signal arrives at the terminal, its signal strength shall not be lower than - 20 /-30dBm (when the terminal can reserve the harvested energy). These requirements and limitations make it a challenge to build zero-power communication networks to provide sufficient coverage. As analyzed in Section 4.1, when the base station directly supplies energy to the terminal, 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 zero-power terminals. 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 terminal, 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 zero-power 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 to for wireless power supply, so its complexity and deployment cost will be much lower than that of base station. Therefore, it forms a relatively economic way to deploy zero-power communication 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 case2 in Figure 5.1-1, the zero-power communication network that is centered on smart phones or CPE nodes provides a very attractive short-range personal communication network.

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

To provide sufficient wireless power

For the passive terminal without a battery, when the wireless power supply signal arrives at the terminal, its signal strength shall not be lower than a certain strength such as -20 or-30dBm (when the terminal 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 zero-power consumption terminal, it can further be investigated whether there are differences in the efficiency for different waveforms, and design reasonable waveforms based on that.

Stability of wireless power supply

When the zero-power terminal 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 the point of view of power supply stability, 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 considered when selecting coding and modulation scheme.

Compatibility with other systems

When the zero-power communication system is deployed in the same frequency band as other systems, the impact on other systems needs to be considered. For example, generally the wireless power supply signal needs to be transmitted with a 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 backscattering transmission, the sine wave signal at a single frequency is an ideal candidate. However, when the power sourcing signal which has experienced amplitude or phase modulation goes further through 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 function of wireless power supply 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 zero-power communication networks. The network nodes in zero-power communication can allocate (transmit) or schedule wireless power according to the communication requirements, so that the battery-less terminal can still complete the wireless communication function. From the perspective of energy management, zero-power communication network changes the power supply from a distributed manner for traditional terminals into the centralized manner for zero-power terminals. From the point of view of power consumption, 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 zero-power communication networks so as to enable green and low-carbon communication networks.

5.2 Challenges of Zero-power Data Transmission

In zero-power communication scenarios, due to the simplified terminal structure, extremely low terminal capacity and extremely low data transmission power constraints, it is necessary to design reasonable data transmission modulation and coding schemes. The allocation of data resources for zero-power terminals should also consider the limitations of the above factors. The challenges brought by diversified communication scenarios should be taken into account.

5.2.1 Modulation and coding for zero-power communication

With the development of wireless communication technology and the improvement of component technology, more and more complex signal modulation technology 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 1024 QAM 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 have 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 Internet of things, such as MTC, NB-IoT and RedCap, although the terminal capability is significantly reduced compared with LTE terminal or NR terminal, 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 common modulation and coding methods for ordinary terminals are great challenges for zero-power terminals. As described in chapter 3, the zero-power terminal has a simple RF and baseband structure, while it needs to transmit data in an ultra-low power mode. Therefore, these two aspects will bring strong constraints to the signal modulation and coding methods to zero-power terminals. Specifically, the simple RF and baseband structures make it difficult for zero-power terminals to realize phase and amplitude modulation and de-modulation at the same time. It is difficult 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 code are difficult to be supported for zero-power terminals while pursuing extremely low complexity and low power consumption.

As described in chapter 3, load modulation technology can be well combined with backscattering technology, so that the terminal realizes ASK, FSK or PSK modulation mode with extremely simple hardware structure and realizes backscattering transmission. Using load modulation technology, the zero-power terminal only needs the ability to adjust its circuit impedance, capacitance or phase delay on the hardware to realize signal modulation and backscattering transmission. On the other hand, simple signals such as ASK, FSK or PSK can also be realized through simple hardware structure. For example, as mentioned in chapter 3, the demodulation of ASK can be realized through a comparator, which avoids complex baseband signal processing and greatly reduces terminal power consumption.

The channel coding of zero-power terminal also needs to match the hardware and software capabilities of zero-power terminal. 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 top of the above, we can further explore whether more complex signal modulation technologies and coding methods can be further supported under the conditions of minimal terminal hardware and extremely low power constraints, such as QPSK.

5.2.2 Multiple access

For different scenarios, zero-power communication system needs to support different number of terminals. Within the coverage of zero-power communication network, multiple terminals may be activated and communicate with network equipment at the same time. Therefore, if reasonable multiple access mode is not introduced, the backscattering signals of multiple terminals will interfere with each other. The network cannot distinguish the overlapped backscattering signals from different terminals. Therefore, zero-power communication systems need to support efficient multiple access scheme. Common multi-access methods include TDMA, FDMA, CDMA and NOMA. In this section, we will discuss the multiple access schemes suitable for zero-power communication.

As shown in Figure 5.2-1, TDM can be used as a candidate multiple access for zero-power communication. Time units are divided in time domain. Different terminals can carry out backscattering communication on different time units based on different time delays. Different time units isolate backscattering signals from different terminals thus avoids mutual interference of different terminals. TDM only need to determine a certain time delay and communicate at the corresponding time slot, so TDM is simple and feasible schee for zero-power terminals.

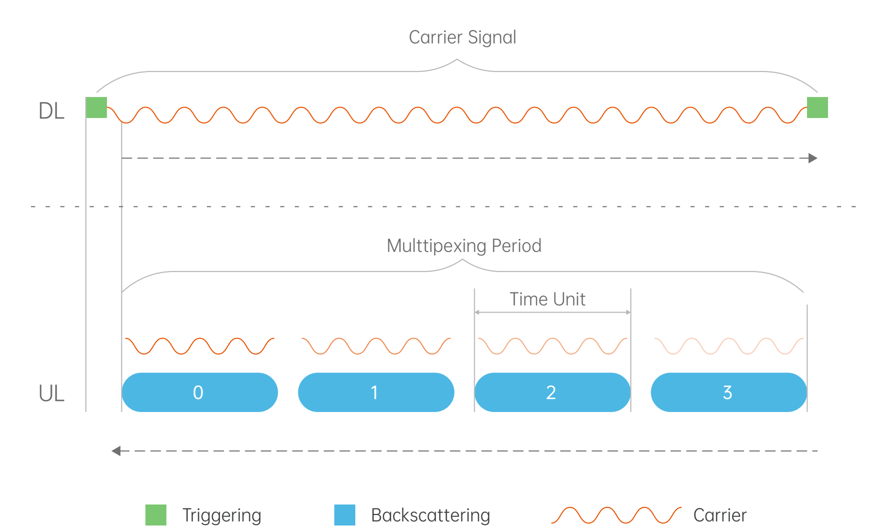

Figure 5.2-1 TDMA-based zero-power communication

Frequency division multiple access (FDMA) is to divide several channels in the frequency domain and communicate with different users using different frequency channel resources. For zero-power communication, it needs to investigate the feasibility of using FDMA. For example, the following shall be considered:

Does the hardware of a zero-power terminal device have the ability to work on different frequency channels?

Multiuser multiplexing using FDMA requires that the terminal has the ability to work on different frequency channels. Such simple requirement for ordinary terminals may have challenges for zero-power terminals. Limited by the hardware complexity and ultra-low power consumption, it is difficult to use high-precision crystal oscillator and high-precision phase-locked loop for zero-power terminal. Therefore, how to achieve low-complexity and low-power frequency generation and then work at different frequency will be an significant challenge for zero-power terminal.

Interference between terminals in different channels

Zero-power terminals send signals to network devices based on backscattering. Also limited by the complexity of devices and circuits, there is no complex shaping filtering for the backscattering signal, so there may be adjacent channel interference. It is also worth discussing how to ensure the simultaneous and reliable communication of multiple channels in case of the existence of adjacent channel interference caused by low complexity implementations. For example, reasonable reservation of guard band and proper receiver design can be considered.

Impact on UE access process

Zero-power terminal works in a passive mode. Before communication , it is necessary for the terminal to obtain energy to drive its circuit . Therefore, different from the traditional communication system where the communication process can be initiated by network equipment or terminal equipment, the communication process is generally initiated by network equipment for zero-power communication. In addition, traditional terminal actively searches the network through the cell search process. The zero-power terminal is in a sleeping state before the wireless power sourcing is provided by the network, so it can only wait to be activated by the network .

When it supports work on different frequency channels for zero-power terminal, how to efficiently trigger the communication process of network devices is another problem needs to be considered. For example, how does network equipment efficiently search the channel where the terminal camps? How to provide sufficient and efficient power supply?

Code division multiple access (CDMA) is a conventional multi-access mode in traditional communication system. On the same time and frequency resources, it supports multiple users to communicate with orthogonal multiplexing code words. Therefore, CDMA has the advantages of strong anti-interference ability, strong anti-fading ability, good confidentiality and large system capacity. For zero-power communication, if CDMA can be used, it is beneficial to eliminate inter-user interference, effectively improve system capacity and effectively improve communication performance. In particular, since the signal power level of zero-power communication is generally weak due to the use of backscattering communication, the use of CDMA spread spectrum communication can also help to improve the cell coverage.

However, zero-power communication using CDMA transmission may also encounter significant technical challenges. It has higher requirements for the synchronization among multiple terminals, and it also has certain requirements for the power difference of the reflected signals from multiple terminals. On the other hand, due to the ultra-low complexity implementation, it does not have a high-precision clock generation structure, so the ability to maintain synchronization is weak. Limited by the basic signal generation mechanism of backscattering, it is also difficult to implement flexible power control before signal transmission. Therefore, how to effectively realize CDMA transmission needs to be further considered.

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

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

The first challenge of zero-power communication is the restriction of power supply. 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 zero-power terminal, 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 meet 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 zero-power communication system needs to avoid the interference between users, inter cell interference and the interference of different systems on zero-power communication, so as to make the zero-power data transmission under ideal conditions and avoid data retransmission as much as possible. On the other hand, the data transmission of zero-power communication also needs to rely on the reasonably designed power supply signal and efficient cooperation between the power supply process and the data transmission process.

The second challenge for zero-power communication is to support data transmission from a large number of terminals within a very short communication time. For example, for logistics scenarios, data reading and reporting from thousands or even tens of thousands of zero-power terminals 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 zero-power communication is triggered by network, all terminals are unknown to the network. A reasonable system access and communication procedure is needed to enable a large number of zero-power terminals to be quickly identified and scheduled for efficient data transmission. For this reason, in a zero-power communication 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 zero-power communication. As shown in Figure 5.2-2, data transmission for different zero-power terminals 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.

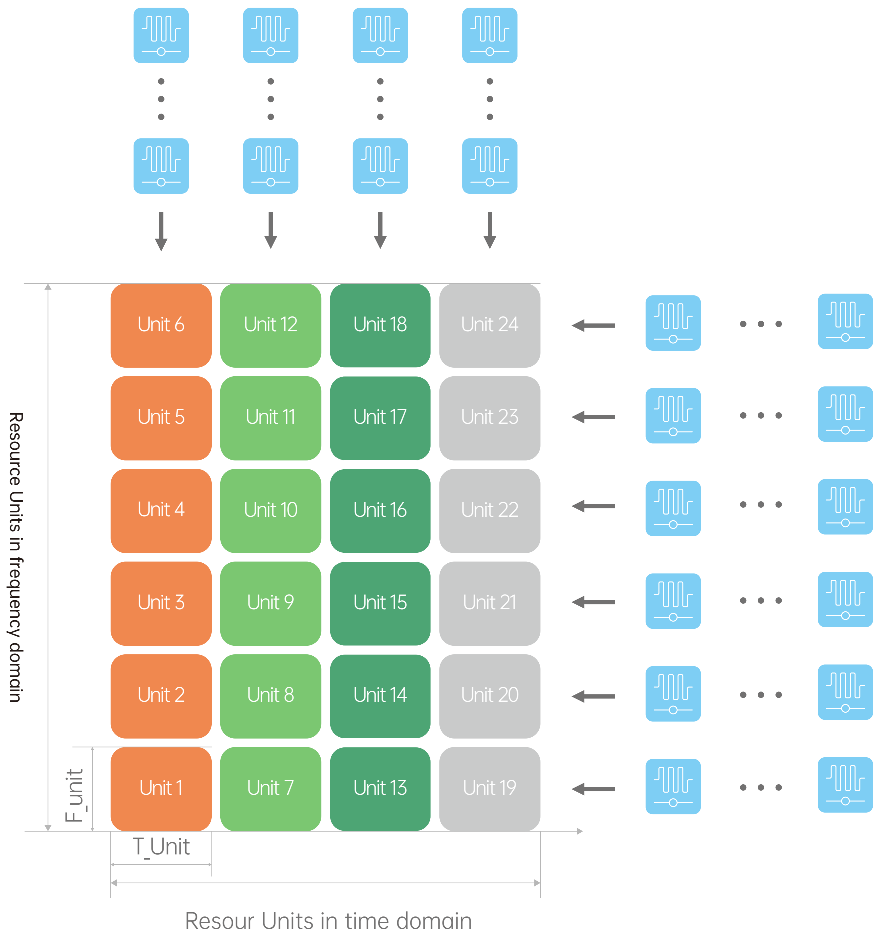

Figure 5.2-2 Resource allocation for Zero-Power communication

The third challenge in zero-power communication is the impact of ultra-low cost and complexity of zero-power terminals on data transmission.

Firstly, the resource utilization capacity of zero-power terminal 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 zero-power terminals 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. A compromise is required between the flexibility of resource allocation and the capability of zero-power terminals. Networks can allocate relatively less-flexible resources for zero-power terminals. As shown in Figure 5.2-2, the network configures multiple relatively fixed resource units for zero-power terminals in a certain mapping manner. The frequent changing of the mapped resource units should be avoided for a zero-power terminal to reduce the complexity of resource allocation.

Secondly, the weak synchronization capability of zero-power terminal 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 high requirement of synchronization. Traditional terminals, such as smartphones, MTC devices and other IoT devices, can meet the synchronization requirements of cellular systems. For zero-power terminal 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[1]. Whether the clock accuracy with such large error can meet the timing requirements of zero-power communication and how to adapt to that is problems that needs further study.

Further, for zero-power terminals, 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 zero-power terminal 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.

- If zero-power terminals are unable to obtain stable and high-accuracy clock, several problems are introduced for cellular based zero-power communication:

Interference from uplink transmission

The strict timing for uplink transmission can be achieved by traditional terminals with high accuracy oscillator. It helps the uplink multiplexing of users and reducing uplink inter-user interference. In TDD system, interference between uplink and downlink can also be avoided with aligned timing of network and UEs. Zero-power terminal cannot achieve strict timing of the start and end of the uplink transmission, which may cause the uplink transmission of zero-power terminal to exceed the transmission time location boundary and cause interference to other terminals. In addition, if the zero-power terminal is in a "power-off" state before uplink transmission, it will result in a complete loss of timing thus the timing of the uplink transmission cannot be available anymore.

Downlink performance degrade

In cellular systems, traditional terminals monitor downlink signals, such as reference signals, control signals and data according to their monitoring occasions. The low accuracy and instable clock of zero-power terminal does not allow the monitoring of downlink signals in the exact occasions. Since accurate synchronization of downlink cannot be maintained, the timing of downlink signal may deviate significantly from that of downlink signal sent by network, which will degrade the downlink performance.

The extremely low cost and complexity of zero-power terminals limit their ability to obtain local high-accuracy clocks. In order to support zero-power terminals in cellular system, it is necessary to study how to help zero-power terminals to achieve the required timing, considering the conflict between the requirements of the timing in cellular systems and the poor timing capabilities of zero-power terminals.

5.3 Requirements and Challenges of Lightweight Protocol Stacks

In zero-power communication system, a zero-power terminal needs to collect energy from the radio waves sent by network before it is capable to work. Therefore, zero-power terminal keeps in 'power -off' state, i.e., out-of-service, before energy is obtained.

In some use cases, islanding is observed in the deployment of zero-power network system, where full coverage cannot be achieved. As a result, zero-power terminals are likely to be out-of-service due to lack of coverage, e.g., in logistics and warehousing scenarios.

Therefore, zero-power terminals are disconnected from network when there is no power sourcing or out of coverage. Under such harsh conditions, smaller processing delay, lower memory consumption and more efficient data transmission schemes are required in zero-power communication system.

5.3.1 State management

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

Considering the characteristics of small memory, low processing capacity, battery-less, small data transmission and massive delivery, traditional multiple-layered protocol stack and complicated state management are no longer suitable for zero-power terminals.

For logistics and warehousing scenarios, complicated state management and transition procedures are not needed for terminals 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 zero-power terminals makes the allocation of IP address as 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 system, with the assumption that terminals 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 zero-power communication, due to the dependence on power supply and the limitation of terminal 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 zero-power terminals. According to the above requirements and characteristics, flat protocol stack is worth to be considered. Meanwhile, integration of control plane and user plane can further reduce the complexity of UE and accelerate the procedure of data transmission.

In addition, it can simplify the stack structure for zero-power terminals adaptively according to different use cases. Zero-power terminals have relatively relaxed requirements on data transmission. For example, in warehousing and logistics scenarios, a zero-power terminal only need to report its identification or basic information. Hence complicated protocol stack becomes unnecessary. For this kind of zero-power terminal to support simple information transmission, 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 requirement of mobility, we can further study how to reduce the protocol stack on mobility management.

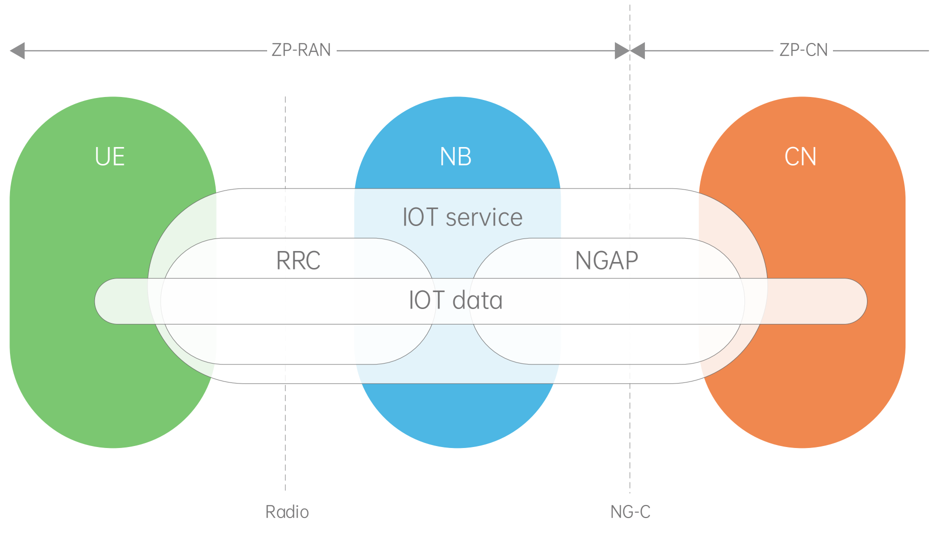

Figure 5.3-1 Lightweight protocol stack

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

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

Therefore, flexible and adaptive protocol stack is promising for zero-power communication.

5.3.3 Mobility Management

For different scenarios, the mobility requirements of zero-power terminals are different based on the mobility characteristics and QoS requirements. For most of scenarios, such as industrial wireless sensing, smart home, warehousing, etc., zero-power terminals 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 zero-power terminals. However, compared with the traditional NR system, if there is no delay requirements and lossless requirements, 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 based on the measurement results of downlink reference signal transmitted by the network.

In zero-power communication, terminals 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, further studies are needed on how to execute necessary mobility management for zero-power terminals.

5.4 The requirements and challenges of lightweight security mechanisms

Similar as in other IoT scenarios, trusted access and secure transmission remain important for zero-power communication. 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 zero-power terminals to use complex security mechanisms as in LTE or NR. Therefore, a lightweight security mechanism suitable for zero-power communication 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 zero-power communications.

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

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 zero-power communication scenario, the computing and transmission resources supported by zero-power devices are very limited. The traditional security mechanism is challenging for zero-power 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

Zero-power communication has different characteristics for downlink and uplink. The downlink channel carries the signaling triggering data transmission and the uplink channel carries the data information. Therefore, the security threats of zero-power communication can be divided into:

1) Downlink threat: false trigger. If a fake base station mis-triggers a zero-power device to perform uplink data transmission, or a forged trigger signaling mis-triggers a zero-power 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.

2)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.

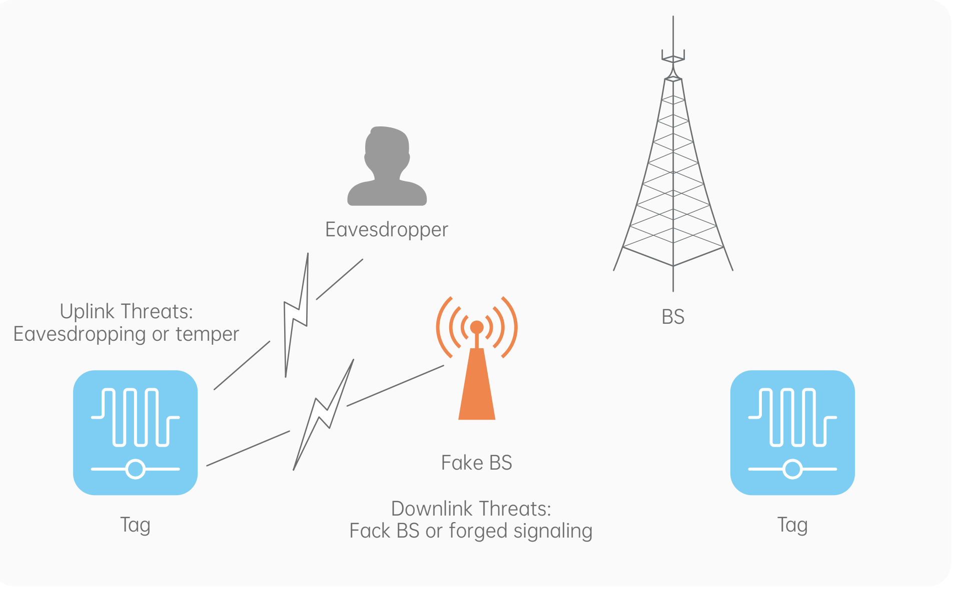

Figure 5.4-1 Security threats of zero-power communication

The advantages of zero-power devices are small size, light weight, low cost thus has a wide range of application scenarios. Zero-power communication 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 zero-power communication can be divided into:

1) Low-cost security requirements: In a zero-power scenario, terminal equipment tends to be extremely simplified, with extremely low power consumption, 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 scheme 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.

2) The requirements of distributed/scenario-diversified authentication and authorization: For logistics/manufacturing and other industry scenarios, zero-power 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 zero-power communication

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 zero-power devices, trusted identity management and reliable secure transmission are mandatory to ensure rights and protections for business, network, and user. 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 zero-power communication scenarios, it is required for the network to be able to manage the zero-power terminals 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 zero-power communication business. On the other hand, it is difficult to reuse the existing complex network architecture for zero-power terminals with minimal terminal capacity, very low power requirements and dependence on wireless power. Therefore, a simplified network architecture suitable for zero-power communication 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 Internet of Things 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 zero-power communication. The main reasons are as follows:

1) Complex network architecture will bring high operating costs to zero-power communication, thus hindering the development of zero-power communication.

2) Complex network architecture will also affect the power consumption of zero-power terminals, which brings new challenges to the power consumption of zero-power terminals.

3) The complex network architecture also makes the network deployment complicated and inflexible, which is not conducive to deploy zero-power communication 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 zero-power communication. The simplified network architecture can simplify the types of network elements and combine network functions, to make the deployment of network elements meet the requirements of zero-power communication, and the interface protocols between different network element types are also as simple as possible.

The following describes the characteristics of a network architecture suitable for zero-power communication.

5.5.2 Support of simplified controlling signaling or transport plane

First of all, zero-power communication 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.

Or, if the default destination data center is configured at the zero-power terminal, the zero-power terminal 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 zero-power communications or services, which can avoid the establishment of a dedicated zero-power data channel for each terminal.

In many cases, zero-power communication 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.

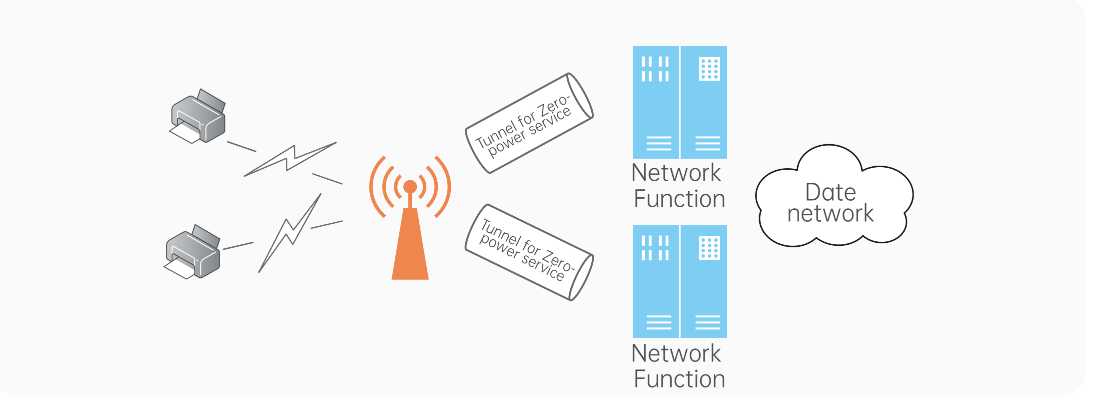

Figure 5.5-1 Simplified tunnel for Zero-power communication

5.5.3 Network architecture supporting hierarchical control

Zero-power terminals can be used in logistics and warehousing. Due to the limited power consumption of zero-power terminals, a hierarchical network architecture can be adopted for zero-power terminals. For example, the zero-power terminal first sends the data to a certain data cache point in logistics or warehousing (data cache points can be installed or deployed in logistics vehicles or inside the warehousing), and the data cache points in logistics or warehousing are periodically or quantitatively reported the data sent by the zero-power communication terminal 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 zero-power terminals at a fixed time or via a paging triggering.

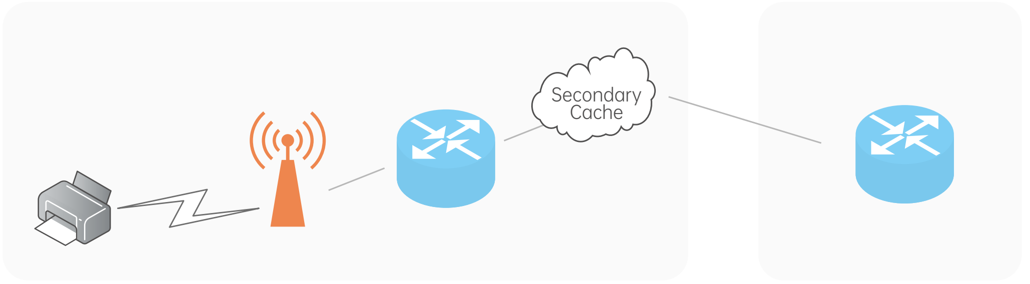

Figure 5.5-2 Network architecture supporting hierarchical control

5.5.4 Support flexible and efficient network selection function

Zero-power communication is mainly used in industrial sensor networks, logistics and smart homes. Therefore, zero-power communication can ignore complex network environments such as roaming scenarios, and the demand for network selection is weakened. Therefore, the zero-power terminal can perform flexible and efficient network selection functions to minimize the power consumption of the zero-power terminal.

5.6 References

[1] Jinhai Zhang, Bo Wang, Yi Peng, Tongning Hu and Xin'an Wang, "A 800nW high-accuracy RC oscillator with resistor calibration for RFID," 2013 IEEE 10th International Conference on ASIC, 2013, pp. 1-4, doi: 10.1109/ASICON.2013.6811876.

[2] 3GPP TS 38.212 V15.9.0

[3] 3GPP TS 38.214 V15.10.0

[4] 3GPP TS 33.401: "System Architecture Evolution (SAE); Security architecture"

[5] 3GPP TS 33.501: "Security architecture and procedures for 5G system"

INTEGRATION OF ZERO-POWER COMMUNICATION AND OTHER KEY TECHNIQUES OF 6G

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, zero-power communication is expected to integrate with other 6G candidate technologies to build a green, energy-efficient, intelligent and efficient mobile communication network.

06

6.1 RIS assisted zero-power communication

Reconfigurable Intelligence Surface (RIS, or Intelligent Reflection Surface, IRS) is composed of reconfigurable units (e.g., information metamaterials) arranged in precise geometric shapes. Each reconfigurable unit is composed of a microcircuit containing a biased diode, or PIN tube, triode, MEMS, graphene, temperature sensitive device, photosensitive components and other materials. The reconfigurable unit of RIS can form different responses to electromagnetic waves as shown in Figure 6.1-1, where the frequency, phase and polarization can be controlled in a manner of reflecting or refracting electromagnetic waves so as to achieve the effects of polarization, backscattering, energy gathering or absorbing.

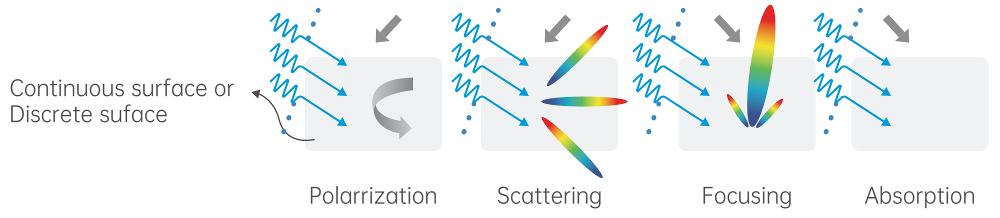

Figure 6.1-1 The characteristic of Reconfigurable Intelligence Surface

RIS technology is considered to be one of the key technologies of 6G. In this section, we will explore the potential combination of RIS and zero-power IoT communication.

Regarding energy harvesting and backscattering, as shown in Figure 6.1-2, RIS can assist zero-power communication in the following aspects: First of all, the energy of the incoming wave can be harvested via RIS to provide zero-power devices with more accurately focused energy beams and higher input power in order to improve the energy conversion efficiency. Secondly, RIS can also receive the reflected signal of zero-power devices (e.g., Tag), realize controllable backscattering by configuring the phase, amplitude, polarization and other parameters of the signal, and forward it to the receiver of the system (e.g., reader in Figure 6.1-2) to improve the reception performance.

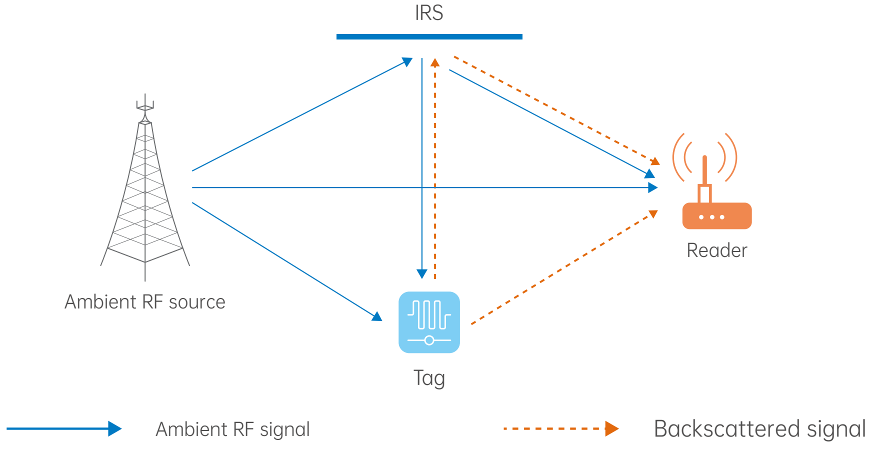

Figure 6.1-2 IRS assisted Ambient Backscatter Communication [1]

The backscattered signal reflected by the zero-power device to the target device can be avoided to be interfered by the environmental signal via RIS, e.g., by using the phase offset of RIS to compensate for the effects of multipath. At the same time, the reconfigurable unit of RIS beamforms the ambient signal with a strong beam to the tag to enhance the backscatter signal while avoiding the interference of the original incident signal. As shown in Figure 6.1-2, in Source-to-RIS-to-Tag link, the introduction of RIS improves the RF power of input signal received by the Tag.

Due to the low power of the reflected signal and the simple non-coherent energy detector in traditional backscattering system, it requires higher demodulation capability of receiver. Since RIS acts as the tag itself or forwards the reflection information of the tag, the enhanced reflection signal is easier to be detected and demodulated by the reader, and the coverage distance is also enhanced, as shown in the Tag-to-RIS-to-Reader link in Figure 6.1-2.

By controlling the propagation direction of the backscattered signal, RIS also provides possible physical layer security solution in zero-power communication. The legitimate receiver can receive the signal correctly, while the signal power in the propagation direction of the eavesdropper is weakened. Thus, the information carried by the backscattered signal can be safely transmitted.

Therefore, in the IRS-Assisted zero-power communication system, RIS can improve signal reception quality and increase communication distance between zero-power devices and readers by maximizing the power of input signal and/or reflected signal of the zero-power terminal. The potential improvement of IRS-Assisted zero-power communication (or IRS-Assisted Ambient Backscatter Communication) can be further investigated.

RIS and zero-power communication systems will provide ultra-low-power IoT solutions in 6G. Regarding energy harvesting, backscattering and low-power computing as the major features of zero-power communication system, how to take advantage of RIS to improve the efficiency of energy collection and conversion, achieve controllable backscatter, and improve the performance of zero-power communication will be important and challenging in future research.

6.2 Integration of zero-power communication and symbiotic radio

In a typical AmBC (Ambient Backscatter Communications) system, zero-power communication terminals can use radio waves in space to realize backscatter communication[4]. As shown in Figure 6.2-1, when a router and an intelligent device in a primary communication system is communicating, zero-power terminal 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 zero-power terminal 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.

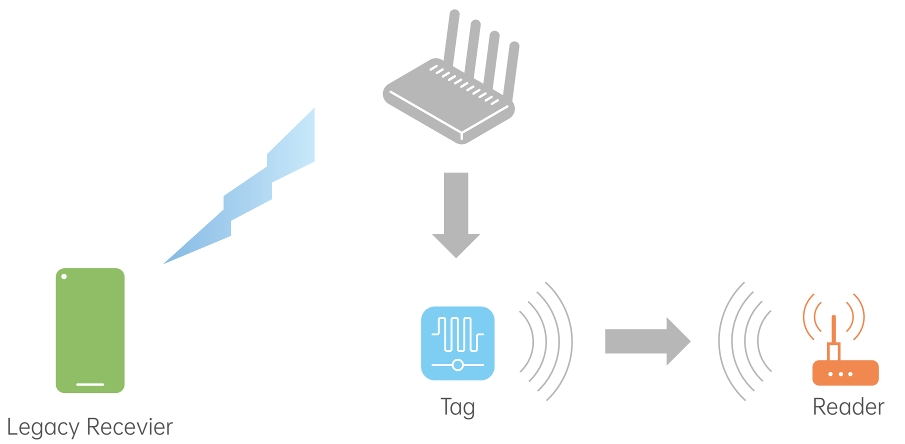

Figure 6.2-1 Illustration of Ambient Backscatter Communications system

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 zero-power communication 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[5]. 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.

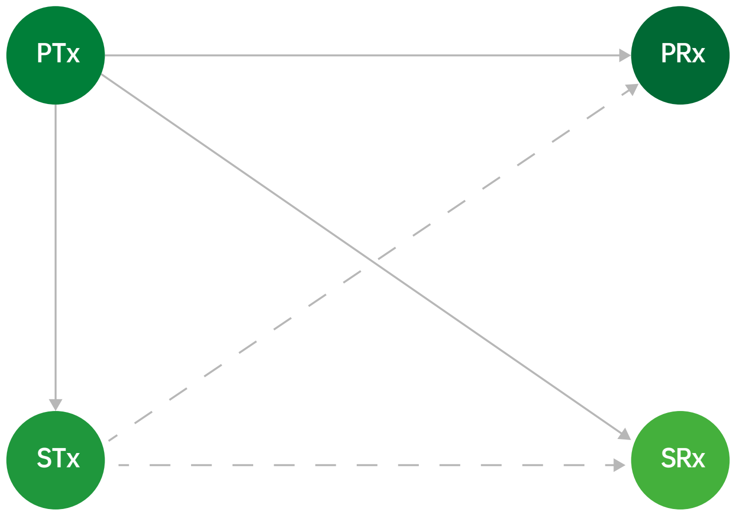

Figure 6.2-2 Symbiotic radio

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[6]. 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[7]. 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.

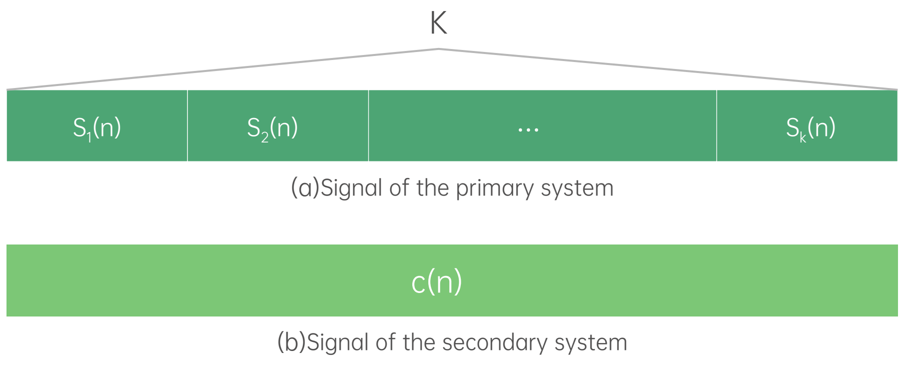

Figure 6.2-3 Relationship between the signals from the primary communication system and the secondary communication system

Symbiotic radio solves the problem of wireless power supply for zero-power communication. In addition, it also extends the source of available spectrum for zero-power communication thus it can share the spectrum for traditional communication. Therefore, symbiotic radio is expected to become an important manner to realize zero-power communication.

6.3 Integration of Zero-power Communication 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 [8].

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 zero-power communication technology (mainly using energy harvesting and backscattering) and ISAC can significantly improve the energy efficiency and meet the green energy saving goal of ISAC [9]. 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 backscattering, 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 [10], using battery-free mobile phone for communication [11], using backscattering assisted vehicle network [5], using backscattering for underwater monitoring [12], using visible backscattering for gesture sensing [13], etc.

Zero-power communication also provides an effective means for ISAC. A zero-power communication unit is installed on the target object, which can trigger the zero-power 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 zero-power 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 zero-power communication 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 [14], 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 [15]. Similarly, a thermoelectric energy harvester is able to detect any changes in surface temperature simply from the variations in the generated energy harvesting signal [16] [17].

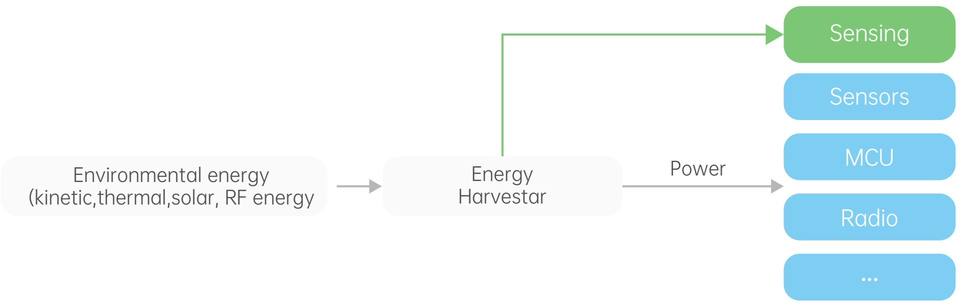

Figure 6.3-1 Application Extension of Energy Harvesting Signal

In recent years, the energy harvesting modes from kinetic, thermoelectric, solar, and RF energy harvesters have been demonstrated to detect a variety of contexts [14]. 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 [14] are shown in Table 6.3-1:

Table 6.3-1 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 fromThermoelectric energy	Water Flow Detection [18] (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 zero-power technology 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 backscattering 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.

6.4 Integration of Zero-power communication and Non-Orthogonal Multiple Access (NOMA)

Compared with orthogonal multiple access technology, NOMA can support the access of multiple devices on the same spectrum/time resources, and is expected to provide high spectrum efficiency and support large-scale connections in future wireless networks. On the other hand, backscatter communication is a new technology. In the future wireless network, the communication between devices can be made possible by using the radio waves in the environment, and battery free transmission can be realized. The integration of zero-power communication and NOMA will help to support the large-scale connection of low-power wireless devices in future networks. Because there is no need to generate carrier signal, the power consumption of zero-power communication is very low and the circuit structure is simple, so it is also expected to realize a very low-cost NOMA scheme.

Firstly, in the downlink of the NOMA system, the performance of the system can be improved by combining with the zero-power technology (the key technologies are energy harvesting and backscattering). At present, the industry has studied the integration of downlink NOMA system and backscatter communication. It can be divided into the following two schemes:

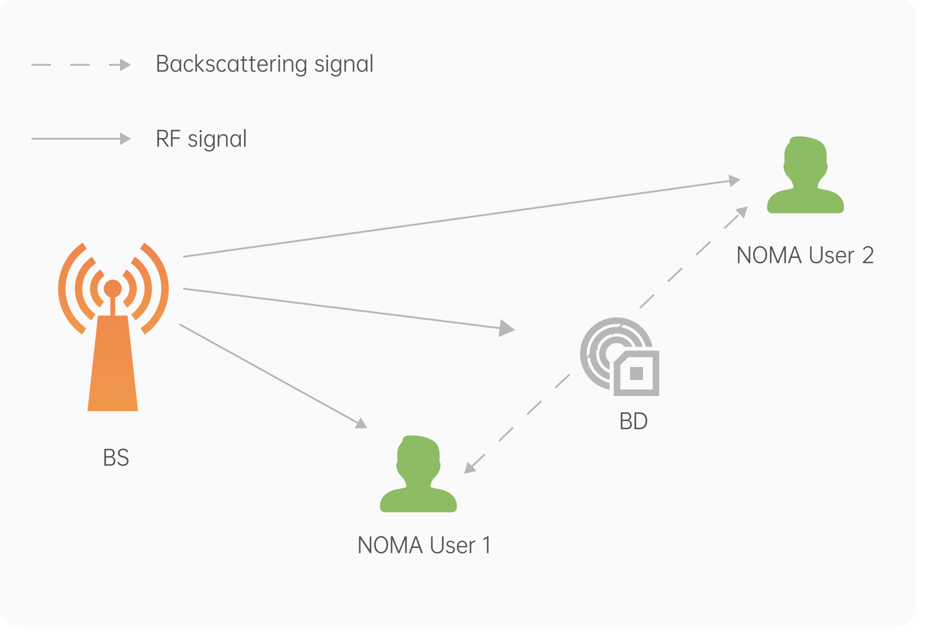

Figure 6.4-1 Downlink NOMA combined with backscatter: use a separate backscatter device

In scheme 1, it combines the downlink NOMA system with a backscatter device using a specific backscatter device [19][20], as shown in Figure 6.4-1. In this backscatter-NOMA system, a base station transmits information to one far-away user 2 and one nearby user 1 simultaneously in the same resource block. Meanwhile, the backscatter device collects energy based on the base station downlink signal and drives the circuit to operate, then it transmits information to the cellular user by reflecting the signals from the received BS signal (backscatter device can choose to only forward base station information or send its own information by modulating base station downlink signals). The far-away user 2 only needs to decode its own information (due to the weak signal strength and attenuation of the backscattered signal, the far-away user can ignore the influence of the backscattered signal), while the nearby user 1 needs to decode the information from both the BS and the backscatter device. For multi-cell scenarios, the energy efficiency of the whole system can be maximized by simultaneously optimizing the total power budget of source, the power allocation coefficient of users and the reflection coefficient of backscatter device [21].

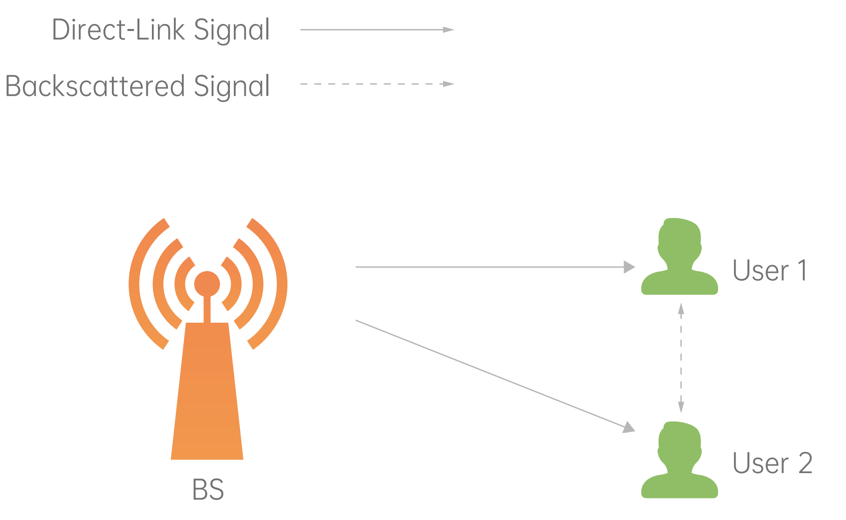

Figure 6.4-2 Backscatter Cooperative Downlink NOMA System

The key idea of scheme 2 is to backscatter the surplus power of the received downlink signals (the part that exceeds the downlink signal energy required for demodulation) at one user to enhance the reception of the user who cannot recover its information (for example, the link quality is poor) [22]. The base station sends messages to multiple users in the same resource block through NOMA. While receiving the signal sent by the base station, the user sends part of the power to other users by backscattering. Compared with the non-cooperative NOMA system, the backscatter-based cooperative NOMA system has higher transmission reliability and efficiency.

Secondly, in zero-power communication, there are often a large number of terminals to communicate. The uplink transmissions of these terminals are usually multiplexed in time or frequency-domain to avoid collisions, yet it is desirable to improve the uplink capacity further. The combination of NOMA technology and uplink transmission of zero-power communication can effectively improve the spectrum efficiency and capacity of the system. At present, the industry has done a lot of research on enhancing backscattering by NOMA technology.

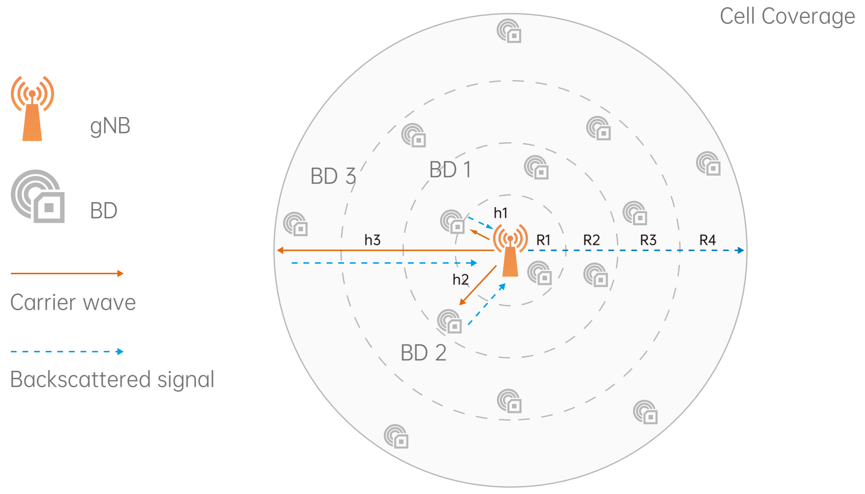

Figure 6.4-3 Power Domain NOMA Enhanced Backscattering Communication

For example, the system performance in terms of outage probability and throughput of backscatter communication system can be enhanced with a hybrid channel access scheme by combining time division multiplexing access (TDMA) with power-domain non-orthogonal multiple access (PD-NOMA). In backscatter communication, the base station (or reader) may receive reflected signals from multiple Backscatter Nodes (BN) during the uplink data transmission. This causes collisions/interference in uplink data transmissions at the receiver. In such an event of data loss due to the collision, it has to be re-transmitted, thereby affecting the energy efficiency of backscatter communication. Therefore, the power domain NOMA can be realized in backscatter communication based on the method of region division [23][24], that is, the network can be reused in different regions or different backscattering power levels to improve the spectrum efficiency of backscatter communication system.

Furthermore, there are also related theoretical studies [25] on how to optimize the interference cancellation in the system combining backscatter communication with NOMA, and how to jointly optimize the transmission power of signal source and the reflection coefficient of backscatter communication to improve the system efficiency.

6.5 Integration of Zero-power Communication 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 [26]. 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 zero-power communication which is based on backscattering, terminals may experience more complicated and stringent communication conditions. As described in section 5.2, 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 zero-power terminals. Without sufficient channel information, how to improve date transmission performance is another challenge. Therefore, AI technology can be considered to improve the performance of zero-power system in these scenarios. Possible directions are listed as follows:

1) Optimizing communication strategy of zero-power terminal with AI/ML [27][28]. 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 zero-power terminals as output, in order to optimize the operation strategy. For example, based on the training results, zero-power terminals can adaptively switch between operations such as energy collection, backscattering, channel estimation and equalization etc. according to different environments. When communicating with network, the terminal 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 zero-power consumption system can be improved with the aid of AI.

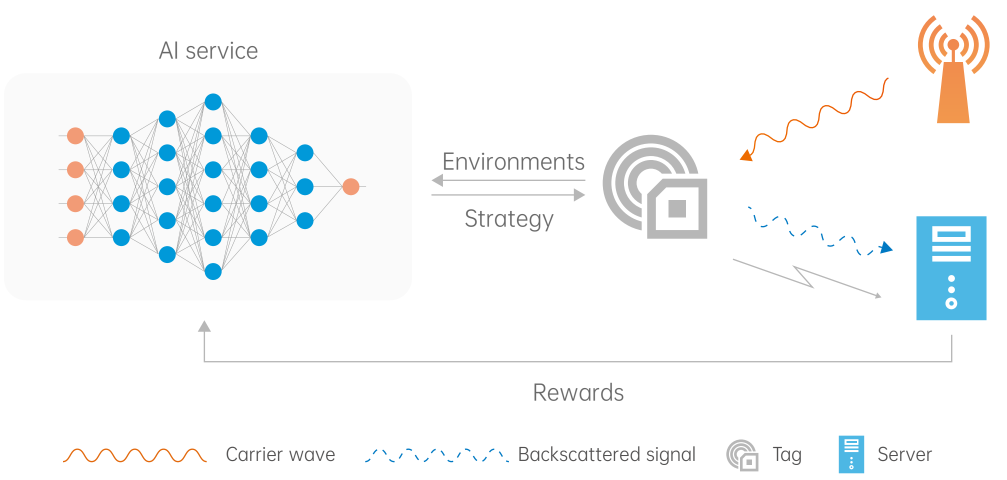

Figure 6.5-1 Optimizing communication strategy of zero-power terminal with AI/ML

2) Optimizing resource allocation method and energy supplying strategy of network with AI/ML [29] [30]. As an example, with the assistance of AI, zero-power 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. Zero-power terminals 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 zero-power terminals, which can be used to improve the performance of AI system. For example, in smart factory scenario, zero-power terminals 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, zero-power terminals 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.

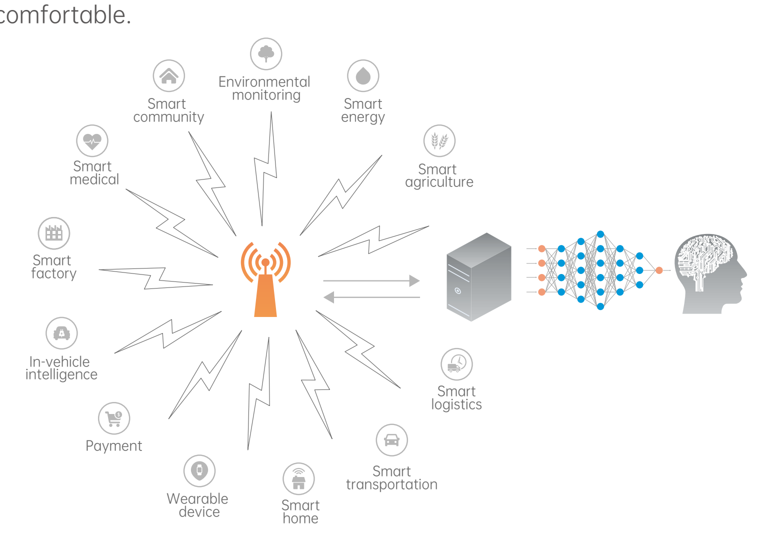

Figure 6.5-2 Low-cost data collection for AI by using zero-power terminals

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Epilogue

In the era of B5G/6G, the demand from the vertical industry will be paid more and more attention. However, although with the rapid development of communication technology, a variety of IoT technologies have been developed to adapt to related industry applications, there are still a large number of application scenarios and their related requirements have not been well fulfilled. Zero-power communication using energy harvesting and backscattering is expected to become a new candidate of next generation of IoT technology because of its excellent characteristics such as extremely low power consumption, very small size, ultra-low cost and so on. In this white paper, it firstly summarizes the potential application scenarios of zero-power communication and presents the key technologies that enable zero-power communication. Then, it makes a systematic analysis on the overall design aspects of the zero-power communication system, such as the available frequency bands, the deployment mode and the coexistence with the traditional communication system. Furthermore, the key technologies and the possible challenges of zero-power communication, such as wireless power supply, data transmission, lightweight protocol, transmission security and network architecture are also systematically considered and analyzed. Finally, it gives an initial analysis on the potential integration of zero-power communication and other 6G technologies.

It is hoped that the white paper "Zero-power Communication" from OPPO Research Institute can play a role of throwing bricks and attracting jade. If it can trigger more thinking about zero-power communication related technologies in the industry and promote the early maturity of related industries, the authors of this book will be relieved and encouraged.