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# 6G Visible Light Communication Technology White Paper

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China Mobile Research Institute

# Preface

With the increasingly stringent communication requirements, more spectrum is urgently needed for mobile communication. Since the spectrum resources below 6GHz has been depleted, and the millimeter-wave frequency bands such as 26GHz and 39GHz have been allocated for 5G use, it is necessary to explore higher frequency bands for communication, such as terahertz communication and visible light communication (VLC), to meet the requirements of higher capacity and ultra-high experience rate. Visible light usually refers to electromagnetic waves of 380~790THz (wavelength ranges is 380~790nm). The candidate spectrum covers about 400THz. The characteristics of large bandwidth and easy to realize ultra-high-speed communication make VLC become a potential supplement to future mobile communication systems.

This white paper aims to discuss the potential application scenarios of VLC in 6G and the communication requirements expected to be met, and proposes the challenges and key technologies of VLC, so as to promote the discussion and thinking in the industry.

The white paper is supported by the partner teams of Fudan University, Beijing University of Posts and Telecommunications, Southeast University, etc. Thanks to the contributions and assistance of researcher Chao Shen and Professor Nan Chi of Fudan University, Dr. Pan Tang and Professor Jianghua Zhang of Beijing University of Posts and Telecommunications, and Professor Jiaheng Wang of Southeast University, etc.

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# 1. Concept

Visible Light Communication (VLC) is a wireless communication method integrating illumination and communication. In VLC systems, visible light source such as light-emitting diode (LED) transmits information with high-speed flashing light that human eye cannot perceive, and photoelectric detector (PD) converts the received optical signal into electrical signal to obtain information [1]. As a new combination mode of illumination and communication, VLC is an effective supplement to the existing wireless radio frequency communication.

## 1.1 Characteristics of VLC

Compared with the traditional radio frequency (RF) communication, VLC mainly has the following advantages:

1) Abundant spectrum: the spectrum resources available for traditional wireless communication are only about 300MHz, while the visible light candidate spectrum bandwidth is nearly 400 THz. Therefore, VLC can effectively solve the problem of increasingly tight spectrum resources.

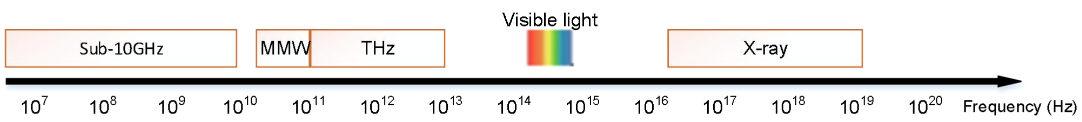


Figure 1-1 Spectrum resource map

2) Easy to deploy: since the existing facilities such as lighting, display and imaging in the illumination industry are mature, transmitting and receiving devices of VLC can be obtained by simple upgrade. Considering illumination requirements, low-cost ultra-dense deployment can be achieved to meet high traffic density requirements.

3) Green and energy-conservation: with the integration of illumination and communication, VLC has the advantages of low power consumption and high energy efficiency. This is exactly in line with the national energy conservation

and emission reduction strategy.

4) Immunity to electromagnetic interference: there is no interference between Visible light and RF signal, so VLC is very suitable for electromagnetic sensitive scenarios such as aircraft, hospital and smart factory to effectively avoid electromagnetic interference and ensure the normal operation of equipment.

However, VLC also has some shortcomings. Due to the characteristics of visible light being easily blocked and having large propagation loss, and the low bandwidth of commercial VLC device, VLC is currently mainly used in short-distance point-to-point communication scenarios with medium or low data rate. On the other hand, the terminal lighting will bring great inconvenience in daily use, so the supported scenarios are limited applying visible light uplink.

## 1.2 **Recent research**

VLC sprouted in China and flourished in Japan [2][3]. Grantham Pang of the University of Hong Kong first proposed the concept of VLC in 1999, and then the research team of M. Nakagawa of Keio University in Japan proposed an access scheme for LED based VLC. Since then, VLC has become a research hotspot in industry and academia. Japan established the Visible Light Communication Consortium (VLCC) in 2003, and numerous VLC application forms such as high-speed interconnection of local area networks, intelligent transportation systems, and intelligent lighthouses have emerged. Europe launched OMEGA (the Home Gigabit Access) program in 2008, aiming to develop indoor interconnection technologies with 1Gbit/s data rate, and VLC is one of the research priorities. In the same year, the U.S. government launched the Smart Lighting Program to explore advanced and innovated technical schemes for VLC system.

Domestic research in VLC started late. After more than ten years of hard work, we finally caught up and reached the same level as the developed countries, and obtained leadership in some directions.

In academia, there are mainly Fudan University, Tsinghua University, Beijing University of Posts and Telecommunications, Southeast University, Institute of Semiconductors, Chinese Academy of Sciences, Taiwan Jiaotong University, etc. participating in VLC research. The research directions include modulation technology, OFDM technology, LED equalization technology, VLC channel modelling, light source layout and so on [4].

In the industry, the national and local governments have increased their investment in the industrial development of VLC. The VLC application products on the market cover many fields such as indoor positioning, APP, secure communication, payment and Internet of Vehicles.

VLC standardization has followed the industry's footsteps. The Institute of Electrical and Electronics Engineers (IEEE) is the first international organization to formulate VLC technical standards. The organization established the VLC working group in 2009 and released the first version of the VLC standard IEEE 802.15.7-2011. This standard has made detailed specifications in VLC modulation mode, networking architecture, physical layer design and so on. In our country, the wireless personal area network standard working group of the National Information Technology Standardization Technical Committee published "White Paper on Standardization of Visible Light Communication" in 2016, and began to formulate related standards. In 2018, series of VLC standards called "Long-distance communication and information exchange between information technology systems Visible Light Communication" have been released.

China Mobile is setting up joint innovation projects with Fudan University, Tsinghua University, Beijing University of Posts and Telecommunications, Southeast University, focusing on core devices of VLC systems for 6G, wireless and visible light fusion networking, air interface transmission schemes of VLC, VLC channel modeling and prototype system for verification.

# 2. Application scenarios and requirements of VLC

## 2.1 Mobile communication scenarios

With the continuous development of mobile network services and the continuous enrichment of the types of network access devices, massive data needs to be accessed by air interface to the core network. Visible light provides the possibility of improving the 6G communication rate with its THz spectrum resources. The ultra-large bandwidth can support more flexible time-frequency resource allocation schemes and multi-user and multi-service transmission modes, which can not only become a new hotspot high-capacity scenario solution but also support high-speed user access in small indoor scenarios. A higher user experience rate can be achieved at the same time. Different from the existing visible light communication application scenarios, mobile communication scenarios need to focus on the user's mobility and environmental variation. Visible light communication needs to provide users with a continuous service experience.

### 2.1.1 Hotspot high-capacity scenarios

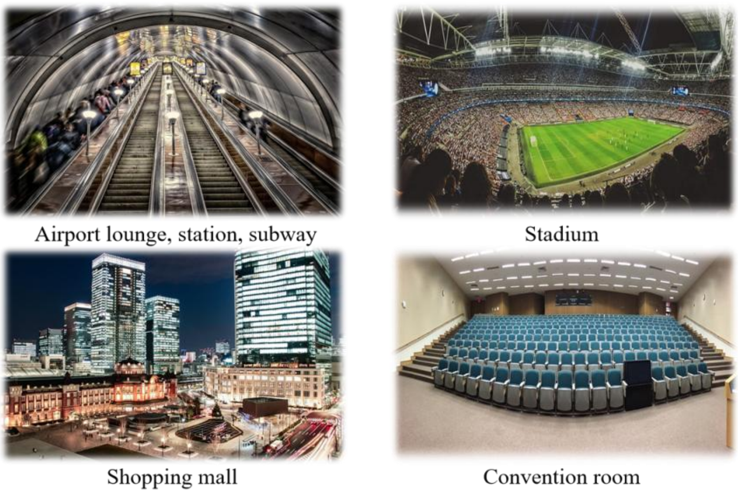


Figure 2-1 Typical hotspot high-capacity scenarios

Hotspot high-capacity scenarios include densely populated transportation hubs, shopping malls, stadiums, large conference rooms, etc. The target group is mainly users holding mobile devices. The main challenges faced by this scenario are light beam tracking and collaborative management, light noise and light interference elimination, and so on.

### 2.1.2 Indoor hot-spot scenarios

Figure 2-2 Typical indoor hot-spot scenarios

Indoor hot-spot scenarios include individual rooms, offices, conference rooms, etc. Such scenarios have a small area, and the user movement area is limited to several meters. In these scenarios, the direction of the light beam does not need to switch frequently, and the control information occupies relatively few resources. More communication resources can be allocated to user data transmission. The primary study items in these scenarios are spectral efficiency improvement and resource scheduling optimization.

## 2.2 Vertical industry communication scenarios

With the further optimization and upgrading of the future industry, the vertical industry has put forward higher security, confidentiality, and reliability requirements for communication indicators. As a new technology integrated with lighting, visible light communication builds a network based on existing lighting nodes. It can avoid the impact of high-power RF signals on the vertical industry's services and improve security. On the other hand, there is a huge frequency gap between the visible light band and the present communication microwave band. The visible light can avoid interference with the existing system during the communication process and improve the robustness of communication.

### 2.2.1 Traffic scenarios


Figure 2-3 Traffic scenarios

Traffic scenarios mainly include ground, aerial and maritime transportation scenarios. In these scenarios, the existing light source in the traffic system could be used to transmit information and reduce the cost of mobile communication network construction. Because visible light communication can also provide positioning function, which will help intelligent traffic management system obtain accurate road information. The main challenges in traffic scenarios include visible light networking and mobility management.

### 2.2.2 Harsh electromagnetic scenarios


Figure 2-4 Harsh electromagnetic scenarios

Harsh electromagnetic scenarios mainly include hospitals, factories, and airplanes. Such scenarios have strict limits on electromagnetic power and frequency bands. By integrating visible light communication equipment and lighting equipment, and the limitation of optical power, it is possible to provide the necessary lighting while effectively avoiding electromagnetic interference and achieving safe and reliable wireless communication. The main challenges in such scenarios are optical power control, etc.

## 2.3 Requirements of VLC

In 2030 and beyond, 6G networks will spawn new application scenarios in three aspects: intelligent life, innovative production, and intelligent society. Their applications include human digital twins, holographic interaction, super transportation, synesthesia interconnection, and intellectual interaction. These scenarios will require terabit-level peak rates, sub-millisecond latency experiences, centimeter-level positioning accuracy, and dozens of times improvements in network energy efficiency [5], as shown in Figures 2-5.

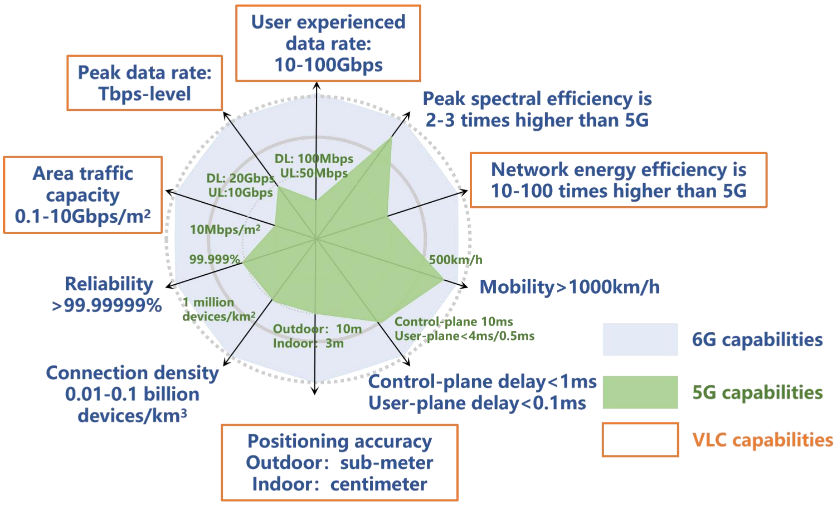


Figure 2-5 The overall requirements for 6G communications

With the help of its vast spectrum potential, visible light communication has become one of the critical candidate technologies for 6G. We expect it to help 6G networks improve user experience rate, peak rate, traffic density, network energy efficiency, and positioning accuracy. However, different scenarios have their respective communication requirements. For example, traffic density and mobility are prioritized requirements in high-capacity scenarios. Small indoor rooms need to improve user experience and peak rates; traffic light integration scenarios need higher positioning accuracy; a harsh electromagnetic environment has strict transmission power and RF leakage power restrictions.

In the future 6G application scenarios, visible light communication must first meet the mobility requirements. By integrating with traditional radio frequency communication (such as low frequency, millimeter wave, terahertz, etc.), visible light communication can provide mobile users with continuous high-rate communication services and a better consumer experience. It's beneficial for visible light communications industry expanding in rapidly way. Besides, it is necessary to achieve communication indicators in Table 2-1.

Table 2-1 Visible light communication indicators

| Indicator names | Values |
|---|---|
| Modulation bandwidth | 5 GHz |
| Peak rate | 50 Gbps |
| Coverage distance | >5 m |
| Capacity density | >100 $Mbps/m^3$ |

# 3. Challenges of VLC

To better meet the requirements of 6G communication, VLC technology is mainly faced with the following challenges at present.

## 3.1 Channel modelling

A wireless channel is a mathematical representation of the wireless electromagnetic environment. It's the foundation of designing a reliable and efficient communication system. It builds an accurate simulation background for system evaluation and optimization. Visible channel modeling needs to consider the frequency, channel fading, space, time, and other wireless channel characteristics.

The visible light band is much higher than the microwave band currently applied. Since the channel characteristics are closely related to the carrier frequency, the visible light channel model doesn't follow the mobile channel model below 100 GHz. In terms of loss characteristics, the frequency increase of visible light will aggravate the propagation loss of the signal and produce atomic absorption effects in the atmosphere. The additional rain and fog decay make the fading model more complicated. In addition, the frequency increase will also reduce the diffraction ability of the optical signal. Deeper shadow fading increases the error of the distance-dependent path loss model, affecting the system evaluation's accuracy. In terms of spatial and time characteristics, the optical signal propagation is limited by the half-power angle of the light source and propagation loss. Thus, the primary propagation mode is Line-of-Sight (LOS), and the secondary propagation mode is Nonline-of-Sight (NLOS). The LOS paths occupy most of the received power. The angular and delay spread decrease significantly. The low spread values indicate the multipath interference is weakened, but it also shows that we need to pay more for the scene coverage. The noise characteristic is another critical feature in visible channel modeling. Due to the small front-end incident power, the background noise, scatter noise, and receiver circuit noise which are common in the environment will impact signal reception. Because noise is random and can be affected by optical communication devices, it isn't easy to quantify and model through experiments, which brings new challenges to channel modeling.

## 3.2 Materials and devices

The current mainstream optical transmitters are LED and laser diode (LD). Although LED is much safer and lower-cost, its frequency response is not ideal. The 3dB bandwidth of the existing commercial LED is generally less than 100MHz, which is far from meeting the required high-speed transmission of 6G. Moreover, LED is nonlinear device, and the nonlinear performance becomes more serious with the increase of transmit power. As for LD, the emitted light is laser of good coherence, and LD bandwidth can reach over 1GHz, meeting the data rate requirement well. However, the transmitter and the receiver need to be aligned in the coupling process, which puts forward high requirements for the stability of the space environment. Also, the laser emitted at high power can pose potential risks to the human eye.

At the receiving end, the visible light signal is generally received by a photodetector (PD). Currently, Positive-Intrinsic-Negative (PIN) photodiodes and Avalanche Photodiodes (APD) are more commonly used. PIN is of relatively low cost, but its sensitivity and frequency response bandwidth are limited, which cannot support high-speed and long-distance VLC systems. APD utilizes the avalanche effect of the diode to multiply the excited photocurrent, and the introduced noise is amplified at the same time, so it is difficult to achieve high signal-to-noise ratio.

To sum up, VLC for 6G place high demands on devices. For the new generation of optical transmitters and receivers, large bandwidth, wide coverage, low cost, convenient coupling, good security, and high sensitivity are required. Therefore, further breakthroughs in the materials and manufacturing process of devices are in urgent need. In order to accelerate the development and selection of devices, it has significant instruction to establish an indicator system for VLC devices.

For light source devices, it is necessary to focus on communication indicators and take lighting indicators into account. Core indicators in communication include modulation bandwidth, power, and linearity. Among them, modulation bandwidth tends to be the bottleneck of the system bandwidth, which is related to many factors such as light source structure and drive circuit. It is the most important indicator. High-speed VLC systems often require the modulation bandwidth of the light source to reach hundreds of MHz or even GHz. In addition, the optical power of the light source has a great influence on the working distance of the system, and is also an important basis for selection. Indicators related to illumination indicators include volt-ampere characteristics dominant electrical indicators, thermal indicators, and a series of optical indicators, such as driving voltage and current, luminous efficiency, brightness, color temperature, stroboscopic and so on. Since driving voltage and current determine the driving circuit design, and affect other indicators such as modulation bandwidth and linearity, they are worthy of attention. Luminous efficiency directly reflects the energy efficiency of the light source, and affects characteristics such as junction temperature. It is also an important parameter.

For detection devices, the main indicators are bandwidth, sensitivity, and spectral response distribution. In addition, factors such as driving voltage and dark current also need to be considered under certain circumstances. Bandwidth of detector directly affects the communication performance of the system, which can reach hundreds of MHz in the industry up to now. In the future, with the development of high-speed VLC systems, the demand for high-bandwidth detectors will be further strengthened. The sensitivity of the detector is also an important indicator, which has a great influence on the working distance of the system. The long-distance VLC system especially requires high-sensitivity detectors such as APD. Besides, the distribution of response to different frequency bands also has a certain influence on the system performance. High sensitivity and large bandwidth in the visible light frequency band are required at the same time.

## 3.3 Transmission

Since the bandwidth of VLC transceivers faces huge challenges, it is necessary to select a suitable modulation scheme to further improve the bandwidth utilization [6]. Single-carrier modulation schemes such as On-Off Keying (OOK), pulse position modulation (PPM), and pulse amplitude modulation (PAM) are of low implementation complexity, but the spectrum efficiency is not high enough. Orthogonal Frequency Division Multiplexing (OFDM) modulation is high spectral-efficient and resistant to multipath effects. The existing OFDM modulation schemes for VLC are of various types, each with its own advantages and disadvantages. How to select a modulation scheme for different kinds of communication scenarios and physical channels needs research. In addition, adoption of high-order modulation in VLC will cause the following problems: signal-to-noise ratio (SNR) needs to be further improved due to the sensitivity to noise of the system; change of the spatial position could result in uneven received power of the quadrature signal; constellation diagram distortion will be introduced due to the nonlinear effect of the visible light emitting device. All the problems need advancements of waveforms and modulation schemes.

Furthermore, the bandwidth of VLC transceivers is affected by the frequency response characteristics. To solve the problem of significant difference in frequency response characteristics between high and low frequency bands, the common solutions are equalization and bit energy loading. Equalization scheme can make the frequency response of the entire bandwidth almost the same. Bit energy loading scheme divides the entire bandwidth into several subbands, the power of which is consistent. An optimal modulation order is selected for each subband to maximize the capacity.

Multiple Input Multiple Output (MIMO) technology is an important technology for VLC in the future. Under the condition of limited bandwidth, MIMO improves the overall communication rate by spatial multiplexing. MIMO system has multiple transmitters and multiple receivers. On the one hand, it can achieve higher capacity and improve the data rate by spatial multiplexing. On the other hand, it can solve the occlusion problem in VLC caused by user movement and complex environment. However, in VLC MIMO systems, the MIMO channel has strong spatial correlation, because the size of the receiver is much larger than the signal wavelength. And the signals from multiple light sources can easily interfere with each other, which affects the overall transmission rate. Therefore, how to design a reasonable spatial decorrelation algorithm at the receiving end is a key problem that needs to be overcome.

## 3.4 Networking

VLC can take advantage of its characteristics of low power consumption, low cost, and easy to deploy, combined with lighting functions, to achieve wider coverage through the ultra-dense deployment of visible light nodes. However, vision light access points have a higher density and are closer to the user than traditional RF communication. If the visible light network adopts the common cellular architecture in mobile communication, there will be problems such as frequent handover, low spectral efficiency and complex interference management. On the other hand, the ultra-dense deployment of visible light nodes also increases the requirements and deployment difficulty of fronthaul and backhaul.

In addition, VLC has the problems of difficult uplink implementation, easy downlink interruption and poor mobility, which greatly limit the application scenarios of independent VLC. It is necessary to consider VLC as a part of the mobile cellular communication network to realize the integration of VLC and traditional RF communication in the cellular network, so as to have the ability to support mobile services and form an industrial scale.

# 4. Key technologies in VLC

## 4.1 Channel modeling

### 4.1.1 Recent research of VLC channel modeling

The equivalent baseband model of VLC can be represented by the following formula:

$$y(t) = Rx(t) \otimes h(t) + n(t)$$

where the channel impulse response (CIR) $h(t)$ can be used to characterize the channel characteristics. It can also be used to analyze the impact of channel distortion. $n(t)$ is the noise. Depending on the different modeling methods, the VLC channel modeling can be divided into two types: theory-based and measurement-based.

### 4.1.2 Theory-based VLC channel modeling

The theory model of CIR includes two types: deterministic channel model and stochastic channel model [7]. The deterministic channel model is a detail description of specific propagation environment, channel scenario and location of transceiver, which has a high accuracy. Compared with the deterministic channel model, the latter model reduces the computation complexity and maintain a high flexibility. However, the accuracy is degraded.

The recursive model was first used to describe the CIR of high-order reflection path of wireless infrared communication in deterministic models. It is used to characterize the line of sight (LOS) path of VLC. Besides, the Lambertian radiation model is used to describe LED lighting.

$$R(\phi) = \frac{m+1}{2\pi} cos^{m}(\phi)$$

The total CIR is the sum of LOS CIR and NLOS CIR:

$$h(t;S,R) = h^0(t;S,R) + \sum_{k=1}^{\infty} h^k(t;S,R)$$

The LOS CIR is represented by a series of delayed impulse functions:

$$h^0(t) = \frac{(m+1)A}{2\pi D^2} cos^m(\phi)\delta(t - \frac{D}{c})$$

In the calculation of NLOS path, the reflection surface is divided into small Lambertian reflection units $\varepsilon$. Each surface unit can be viewed as the receiving unit and transmitting unit. The impulse response of NLOS can be obtained by traversing high-order reflection path.

$$h^k(t;S,R) = \sum_{i=1}^{N} \rho\varepsilon_i^r h^0(t;S,\varepsilon_i^r) \otimes h^{(k-1)}(t;\varepsilon_i^s,R)$$

The recursive model provides a good idea and high accuracy for the characterization of VLC channel. However, it is less used in theoretical modeling of VLC in practice due to its high time complexity.

On the basis of recursive model, the iterative model changes the order of convolution in high-order reflection path, which can reduce computation:

$$h^k(t;S,R) = \sum_{i=1}^{N} \rho\varepsilon_i^r\, h^{(k-1)}(t;S,\varepsilon_i^r) \otimes h^0(t;\varepsilon_i^s,R)$$

Due to its high accuracy and relatively low time complexity, the iterative model is a commonly used method in the theoretical modeling of VLC channel.

Besides, based on the geometric optic and coherent diffraction theory, the ray tracing-based geometric deterministic modeling utilizes the software (such as Zemax [8]) to analyze the channel under the specific situation. The ray tracing technology ensures the accuracy of specifications of transceiver antenna, the surface reflection characteristic of materials and the geometry of the created environment. Compared with iterative model, the ray tracing software requires a detailed description of the propagation environment, so it cannot be easily applied to other scenarios. But it can restore the actual scenarios more accurately and model complex scenarios more flexibly.

The stochastic model includes geometric-based stochastic model and non-geometric-based stochastic model, where the former includes spherical model (A common approach in VLC noise modeling.), regular-shaped geometric randomness model and Carruthers model, and the latter includes the Monte Carlo Algorithm (MCA), Modified Monte Carlo algorithm (MMCA) and Modified Ceiling Bounce Model (MCBM).

There are three kinds of noise in VLC, which are shot noise, thermal noise and amplifier noise, where the shot noise can also be divided into the signal-dependent part and signal-independent part. For the VLC noise modeling, there are two typical methods: one is the equivalent noise source method, where the thermal noise and amplifier noise are unified as the circuit thermal noise [9]. The other is to model these three noises separately [10]. Both methods are commonly used in VLC system analysis. However, there is still necessary to verify the accuracy and applicability of these two models.

### 4.1.3 Measurement-based VLC channel modeling

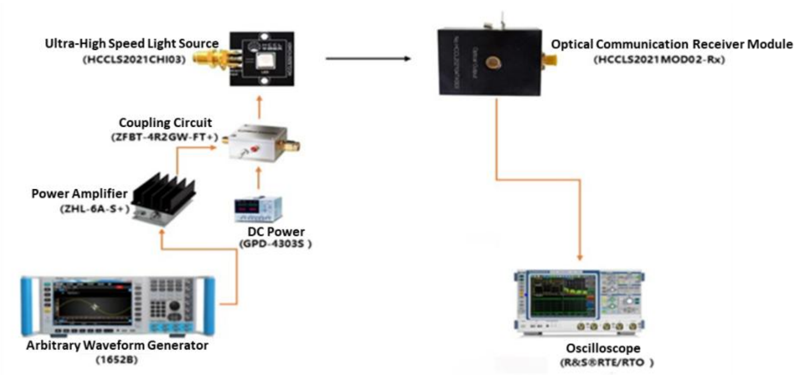


Figure 4-1 VLC Measurement Platform

Measurement-based VLC modeling uses the VLC measurement platform to collect measurement data in practice. Based on the pseudo-random sequence correlation principle, the transmitter sends a pseudo-random sequence. After OOK or quadrature amplitude modulation (QAM), LED will convert the information to an intensity variation. The receiver detects the signal strength through PD, and decorrelates the information to obtain the CIR.

Since the channel impulse response can be obtained directly from the time domain response or obtained by inverse Fourier transform from the frequency domain response, the VLC measurement platform can also be divided into two categories: time domain (TD) detection and frequency domain (FD) detection. In TD detection, the transmitter sends the PN code with arbitrary waveform generator and the receiver decorrelates the TD signal sampled by oscilloscope to obtain the CIR. In FD detection, the transmitter uses a port of vector analyzer to send a frequency sweep signal. The second port of vector analyzer will receive the signal after channel, so that the channel frequency response (CFR) can be obtained. CIR is the inverse Fourier transform of CFR.

Some researches have been carried out for the measurement of VLC channel [11] compared the characteristics of millimeter-wave and visible light channels in a parking lot. They found that the frequency response of the millimeter-wave channel is easily affected by the parking lot structural and surrounding vehicles, while the frequency response of the VLC channel is not greatly affected by these two reasons. The main limitation of VLC measurement platform is the device performance. Reference [12] studied the impacts of human body occlusion on received power and RMS delay in indoor scenario. Reference [13] measured the CIR and path loss in indoor scenario. And references [14][15] studied the impact of different weather on the VLC system in the vehicle-to-vehicle scenario.

At present, there is no measurement work for VLC noise, and there is a lack of actual measurement and verification of theoretical VLC channel noise model. The actual noise distribution in VLC is still a problem that needs to be solved.

## 4.2 **Key devices**

### 4.2.1 Transmitter

The transmitter in VLC systems generally uses white light as the light source, and the light source mainly includes LED, PD and Superluminescent Diode (SLD).

●**LED**

The modulation bandwidth of LED is an important determinant of the channel capacity and transmission rate of VLC system. In order to meet the requirements of 6G-oriented visible light communication, the next generation led needs to improve the modulation bandwidth.

Phosphor white-light LEDs is a commonly used led in visible light system. The blue LED chip emits blue light， and part of the blue light excites the phosphor to produce yellow light, which is mixed to obtain white light. This type of white-light LED is limited by the fluorescence lifetime of its phosphor (such as CE: YAG), so its bandwidth is generally limited to about 2MHz. In order to alleviate the influence of the long fluorescence lifetime, a blue light filter can be added in front of the detector, so that only the blue light radiated by the LED chip itself reaches the detector, thereby increasing the bandwidth of the component. However, since only part of the light reaches the detector, the optical power received by the detector is reduced and the communication distance is limited.

The multi-color chip white-light LEDs can also improve the modulation bandwidth, which encapsulates multiple color chips together to form a white light source, and the more common is the RGB three-color chip white-light LED. The multi-color chip does not have the problem of long fluorescence lifetime, and the wavelength division multiplexing technology is used to modulate each monochromatic light chip in the white light components separately, and transmit multiple signals in parallel, which can greatly improve the channel capacity. Unfortunately, it will increase the complexity of driving design, and also affect the color temperature of white light after combining.

In addition to using different monochromatic light to improve the transmission rate of the component, Micro-LED as the emission source of the visible light system can also greatly improve the modulation bandwidth of the component. The main reason is that the reduction of the active area greatly increases the current density of the carriers in the active area and shortens the carrier life in the active area. At the same time, the smaller active area reduces the junction capacitance of the component, thereby reducing the RC time constant. We can increase the modulation bandwidth of the component while ensuring the total output power by fabricating a Micro-LED array.

- **LD**

LD has a higher modulation bandwidth and thus has a faster information transmission rate. At present, the modulation bandwidth of commercial LDs can reach 2.6 GHz, which is two orders of magnitude higher than that of commercial LEDs. Compared with LED, LD has the advantages of fast response, direct modulation and high coupling efficiency.

- **SLD**

Based on spontaneous radiation and amplified spontaneous radiation, SLD is a component between LED and LD, which has the characteristics of broad spectrum, weak temporal coherence, low noise intensity, and high efficiency. Compared with LED, SLD has higher modulation bandwidth and luminous efficiency. Compared with LD, it does not form a laser with great power density, which is harmful to human eyes, and has a wider spectrum, which is more suitable for lighting.

Table 4-1 Comparison of Different Types of Light Sources

| Type of light source | Linewidth | Method of photon generation | Coherence length | Divergence angle | Modulation bandwidth |
|---|---|---|---|---|---|
| LED | wide | spontaneous radiation | short | large | low |
| LD | narrow | amplified spontaneous radiation | long | small | high |
| SLD | middle | stimulated | middle | middle | middle |

| | | | | | |
|---|---|---|---|---|---|
| | | radiation | | | |

The development trend of different light source types:

- The basic bandwidth of phosphor-based WLED is difficult to increase, and it needs to rely on equalization technology and filters. The only advantage is low cost, and it is not recommended as a future research focus.
- Multicolor LED have good technical maturity, flexibility and industrial foundation, and can be used as a focus component in the initial stage.
- Micro-LED can achieve high basic bandwidth, but the total power is low, and the high-power technology is not mature. Its application in the field of lighting has certain challenges, which can be focused on in the future.
- SLD can basically be attributed to the category of special high-bandwidth LEDs, in which stimulated radiation dominates, and the bandwidth characteristics are ideal.

### 4.2.2 Receiver

The common visible light detectors include PIN photodetectors, avalanche photodiode (APD) photodetectors, and metal-semiconductor-metal (MSM) photodetectors. Their mainly used materials are silicon (Si), germanium (Ge), silicon carbide (SiC), gallium nitride (GaN), aluminum nitride (AlN), perovskite, and so on.

- **Si-based photodetectors**

Si-based photodetectors are widely used in communication in the visible light band because the detection band of Si materials is between 400-1100 nm. The most popular silicon-based detectors are PIN photodetectors and APD photodetectors. PIN photodiode detectors have a lower cost. But their sensitivity and the response bandwidth are limited, which cannot meet the requirement for long-distance communication. Compared with the Si-based detector, APD photodetectors have higher sensitivity (internal gain up to $10^2$~$10^4$), higher response speed, and wider frequency band (frequency band bandwidth up to 100 GHz). But they may introduce considerable noise and have poor stability in high/low temperatures. So they are not suitable for scenarios with high signal-to-noise ratios or significant temperature differences.

- **III-V photodetectors**

Compared with Si-based semiconductors, III-V compound semiconductors have the advantages of high carrier mobility, high direct energy gap, adjustable band gap, and good stability. InGaN detectors using third-generation semiconductor InGaN materials can realize optical signal detection throughout the whole visible light band because of their adjustable band gap. It can be integrated with the same optical communication system to achieve efficient reception of optical signals by matching LED light sources. With the development of zero bias self-drive detector research, the operating voltage of InGaN-based detectors can reduce to zero, making the device work with low power consumption.

MSM photodetectors resemble back-to-back Schottky photodiodes. When the applied bias voltage increases and an avalanche breaks down of the Schottky diode on the reverse deflection side, the current increases dramatically. MSM photodetectors are responsive, simple, compatible with CMOS processes, and easy to integrate. However, the metal on their surface has strong absorption of light, which impacts their internal gain and limits their application scenarios.

- **Perovskite photodetector**

The chemical formulas of Perovskite can be represented as the form of ABX3. The A is a cation divided into organic and inorganic. Organic cation includes CH3NH3+ (referred to as MA+), HC(NH2)2 + (referred to as FA+), while inorganic cation is often Cs+. The B denotes metal cation such as Pb2+, Sn2+, etc. The X represents the halogen anion I-, Cl-, Br-. Perovskites have short response times and higher bandwidths. It has the advantages of being lightweight, having good flexibility, high carrier mobility, large light absorption coefficient, long exciton diffusion length, and adjustable band gap width. They can realize light detection in different bands. However, because perovskites are organic materials, their life and stability are far less than Si and III-V compound semiconductor detectors. The application scenarios are more limited.

PIN and APD are relatively mature. The corresponding commercial products can even reach 1 GHz bandwidth. Their output power can meet various gain requirements. But most Si-based detectors respond at peaks in the infrared band. Although the peak response of the III-V group detector is closer to the visible light band, the sensitivity of the III-V group commercial products is insufficient.

Table 4-2 Comparison of the performance of several photodetectors

| Material | Size (nm) | Bandwidth (nm) | Responsivity (A-W 1) | Detectivity (Jones) |
|---|---|---|---|---|
| Si | 3.0-7.4 | 690-995 | $10^9$ | $\sim10^{13}$ |
| Ge | 2-13 | 980-1200 | 1.5 | $1.2\times10^{11}$ |
| PbS | 2.5-7.2 | 800-1700 | -. | $1.8\times10^{13}$ |
| PbSe | 3-17 | 1200-2500 | 0.67 | - |
| PbTe | 2.6-8.3 | 1100-2150 | - | - |
| CdTe/CdS | 6-11 | 480-820 | 0.3 | $1.2\times10^{8}$ |
| InAs | 2-7 | 970-1500 | 3.81 | $2.2\times1O^{10}$ |
| InSb | 33-6.5 | 1300-1850 | - | $3.7\times10^{12}$ |
| $Ag_2S$ | 5.4-10 | 1200 | - | - |
| $MoS_2$ | 3.1-5.9 | 1080-1330 | 0.85 | $8.0\times10^{11}$ |
| CuS | 3-6.5 | 850-1300 | 300 | $1\times10^{13}$ |
| HgTe | 3-12 | 1200-3700 | $23\times10^{-3}$ | $8.7\times10^{11}$ |

The responsivity, response bandwidth, and dark current of a visible light detector are mainly affected by its material and structure. By matching light source and detector/detector array, semi-conductive visible light detectors can adapt to more scenarios. With the development of VLC technology, the effective transmission of information has become particularly important. The new VLC systems will achieve higher transmission efficiency and a wider transmission spectrum, which puts forward higher requirements for detector bandwidth, high sensitivity/response, integration, flexibility, and self-power supplication.

## 4.3 Transmission Technology

### 4.3.1 Transmission Theory

1) Signal Distribution and Capacity Bound

A typical VLC system is shown in Figure 4-2. It can be divided into two parts according to the physical transmitted signals, which are electrical domain and optical domain.

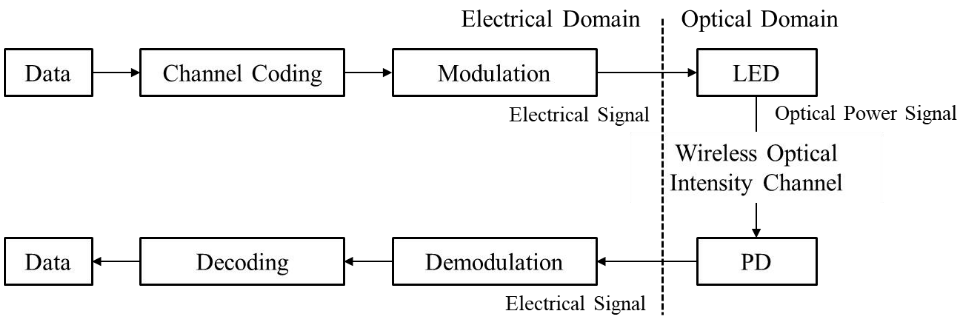


Figure 4-2 VLC Measurement Platform

The data stream generated by the source drives the LED after passing through modules such as channel coding, rate matching, interleaving and modulation. LED converts the input positive signal from the electrical domain to the optical domain, and its amplitude is carried by the optical power. The PD at the receiver converts the signal from the optical domain to the electrical domain to complete the demodulation of the signal. In the linear scale of the LED, the optical power of the LED is approximately proportional to the electrical power, which means that the optical power emitted by LED is proportional to the driving current [16].

Since the physical forms of signals are different, the constraints of different physical signals are also different, so that the analysis of VLC signal distribution can be divided into electrical domain and optical domain. When the signal source is a continuous source, the analysis based on the electrical domain is consistent with RF signal. The optimal distribution of the received electrical signal obeys the Gaussian distribution when the total electrical power is constrained. The analysis of optical domain needs to consider the impact of the LED linear scale and human eye safety.

Therefore, the distribution interval of the optical power signal is a fixed value, and the power of the optical signal is constrained by its first-order moment. The optimal distribution of optical signal obeys an exponential distribution.

The distribution of signal directly affects the system capacity, which could be represented by the performance of capacity bound mathematically. The current researches on VLC signal distribution and capacity bounds are mainly based on the optical domain. The Swiss Federal Institute of Technology Zurich proposed a series of wireless optical communication channel capacity bound from SISO to MIMO [17]. Southeast University and Nanjing University of Posts and Telecommunications have proposed a variety of VLC signal distribution and capacity bounds based on dimming control [18]. Although the analysis of signal distribution on the electrical domain is consistent with RF, it still needs to consider the characteristics of the LED, such as negative values removing and DC bias adding.

Based on the analysis of signal distribution in electrical and optical domain, the generation of VLC signal can be further designed. For example, different distributions can be selected for different channels to obtain better performance. In addition, the capacity bound analysis based on signal distribution can be used for subsequent system design and performance optimization.

2) Signal-Dependent Noise

The received noise of VLC is usually divided into shot noise and circuit thermal noise, where the shot noise can be further divided into relative intensity noise and background light noise [19]. Due to the physical characteristics of the PD and the randomness of the photons emitted by the LED at the transmitter, the actual received noise of the VLC system consists of two parts: signal-independent noise (relative intensity noise) and signal-dependent noise (background light noise and circuit thermal noise).

### 4.3.2 Modulation waveform

The multi-carrier modulation technology can effectively overcome the frequency selection characteristics of the channel, so it is widely used in VLC. There are many multi-carrier modulation schemes based on OFDM. The basic schemes mainly include Direct Current Biased Optical-OFDM (DCO-OFDM), Asymmetrically Clipped Optical-OFDM (ACO-OFDM), Pulse Amplitude Modulation-Discrete Multi Tone (PAM-DMT), etc. Combining the advantages of different modulation schemes, scholars have studied the combination of the above modulation schemes, mainly including LACO-OFDM, ADO-OFDM, HACO-OFDM and so on. The three waveforms ACO-OFDM, DCO-OFDM, and LACO-OFDM are the most representative.

Multi-carrier modulation of VLC requires that the transmitted signal is a non-negative real number. Hermitian symmetry makes the transmitted signal a real number. There are two main ways to generate a non-negative signal : 1) Add DC bias, such as DCO-OFDM; 2) Clips negative signals in the time domain, such as ACO-OFDM, LACO-OFDM. Adding bias does not affect subcarrier utilization, but increases power overhead; clipping does not affect power overhead but wastes bandwidth.

The nonlinear effect of VLC transmitting component will distort the constellation of the signal. Therefore, in order to ensure that the transmitting component works in the linear region, it is necessary to limit the maximum power of the signal. Limiting the maximum power will cause clipping of the signal, resulting in clipping noise. Decreasing the signal amplitude can reduce the clipping noise, but it will also reduce the received signal-to-noise ratio. Therefore, an optimal trade-off between signal amplification and clipping reduction is required to obtain the maximum received signal-to-noise ratio. The coverage performance of ACO-OFDM under low-order modulation is better than DCO-OFDM, while it is the opposite under high-order modulation. Therefore, different waveforms can be selected according to the performance requirements of simultaneous interpreting VLC applications and different transmission channels.

In ACO-OFDM and LACO-OFDM systems, negative signal clipping results in a large number of zeros in the transmitted signal. Due to the influence of noise and interference, the receiver may receive some negative signals. Therefore, filtering the negative signals at the receiver can significantly reduce the noise interference.

The above analysis is instructive for waveform selection in different scenarios and system performance improvement. Further, more waveforms can be analyzed in the future, and the recommended waveforms and clipping ratios in different scenarios can be given, so as to realize high-speed visible light communication transmission.

### 4.3.3 Equalization

The high-frequency response attenuation of VLC transmitting components seriously limits the signal transmission rate. Therefore, it is necessary to use equalization technology to expand the available bandwidth. According to the stage of implementing equalization, equalization can be divided into pre-equalization at the transmitter and post-equalization at the receiver.

Pre-equalization refers to raising the high-frequency part of the signal at the transmitter to widen the available modulation bandwidth. Generally, it is achieved in the frequency domain by applying the inverse function of the system frequency response: A weight is added to each sub-carrier according to the measured response function, so that the amplitude of the low-frequency part is reduced, and the amplitude of the high-frequency part is increased, thereby making the frequency response more flat and achieving the purpose of equalization. The scheme is simple and easy to implement.

Post-equalization refers to compensating for the transmission loss of the signal by transmitting a known signal as a pilot and processing the received signal with an adaptive equalizer. Post-equalization can be divided into time-domain equalization and frequency-domain equalization. Time domain equalization is to consider the impulse response of the time domain, and eliminate the crosstalk between symbols in the time domain through a time domain filter with a finite length tap. The frequency domain equalization is considered from the frequency response, so that the total transfer function after the channel and the equalizer can satisfy the distortion-free transmission. The application of post-equalization technology requires accurate channel estimation, but the uneven frequency response of VLC components will affect the accuracy of channel estimation. In order to estimate the channel more accurately, adaptive pilot design can be adopted to allocate more pilot signals for high-frequency carriers, so as to improve the accuracy of channel estimation and enhance the post equalization performance.

Similar to the equalization technology, the adaptive bit energy loading scheme can also be used to expand the available bandwidth range and improve the bandwidth utilization efficiency.

There are many technical solutions for bandwidth expansion such as equalization and adaptive bit energy loading. In practical application, the appropriate scheme can be selected according to different scenarios, comprehensively considering the factors such as algorithm complexity, engineering implementation difficulty and transmission rate, so as to effectively improve the performance of visible light communication system and improve the data transmission rate.

#### 4.3.4 VLC-MIMO

The illumination and modulation bandwidth of a single LED is limited and insufficient, which makes it difficult to meet indoor illumination requirement and communication requirement. Therefore, LED integration is usually adopted in practical deployment, where multiple LEDs are formed into LED arrays, and multiple LED arrays are deployed in practice. As one of the important technologies of VLC, the MIMO transmission using multiple LED arrays can significantly increase the capacity, overcome the occlusion problem and indoor blind spot problem caused by mobility, improve communication quality, and reduce the difficulty of physical alignment [20].

1) Classification of VLC-MIMO

According to whether the receiver equips imaging lens, VLC-MIMO can be divided into non-imaging MIMO and imaging MIMO, as shown in Figure 4-3.

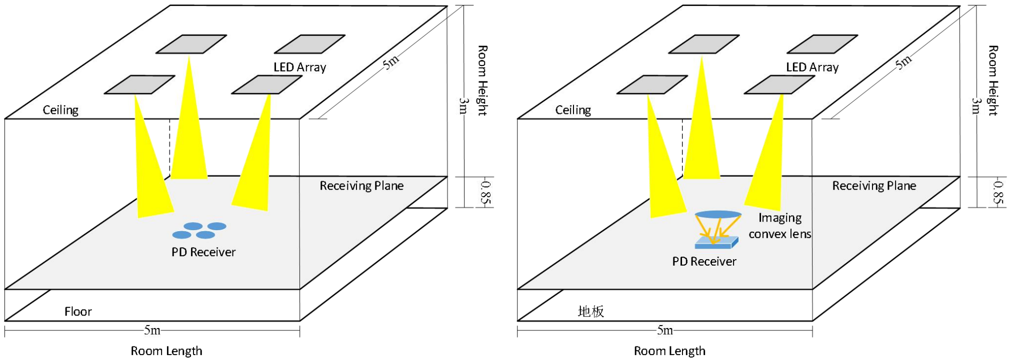


Figure 4-3 non-imaging MIMO (left) and imaging MIMO (right)

The difference between non-imaging MIMO and imaging MIMO is mainly at the receiver. Non-imaging MIMO is similar to traditional MIMO technology. However, since VLC signal does not contain phase information, the VLC-MIMO channel correlation is very large. For example, when the PD is located at the center or axis of the room, the channel matrix may not be full of rank, and the gain and delay of multiple subchannels are the same. Moreover, due to the limitation of space and equipment installation complexity, it is difficult to realize multi-stream transmission in the same LED array. Therefore, each LED array usually transmits different data stream in VLC-MIMO transmission, while different LEDs in the same LED array transmit the same data stream.

Imaging MIMO is a good solution to the solve the location limitations of non-imaging MIMO. In the imaging MIMO system, the imaging lens projects the image of the LED array on the receiving imaging sensor detector array. The use of imaging lenses reduces the receiver size compared to the concentrator used in non-imaging MIMO. The imaging sensor detector array consists of multiple detector pixels, and the projected image will hit multiple pixels on the array to excite current. Each pixel can be regarded as a receiver, so the channel from each pixel to the LED array constitutes a channel matrix. The sensor detector array is composed of a large number of PDs, and the pixels refer to the effective area that the receiver could identify, so a pixel point may contain one or more PDs. Even if the received image is overlapping, the receiver can still restore the signal by some specific algorithms. However, limited by the refresh speed of the detection array, it is difficult to further improve the transmission rate.

According to the transmitter, VLC-MIMO also includes the transmitted lens-based MIMO, as shown in Figure 4-4.

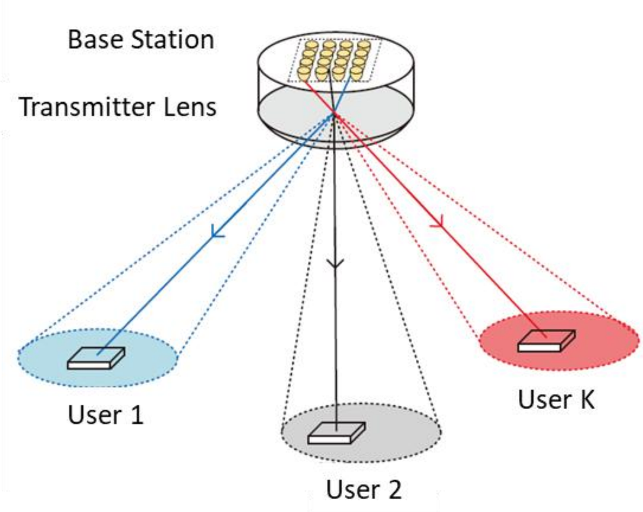


Figure 4-4 VLC-MIMO system with transmitted lens

The transmitted lens-based VLC-MIMO uses the transmitted lens to refract the light emitted by different LEDs to different directions and angles, so as to realize the energy concentration and improve the spatial resolution. The light emitted by the LED is firstly refracted on the lens, and then refracted on the spherical surface of lens, so the transmitted lens can be used to distinguish different light signals. The light will be refracted by lens and concentrate into a small angle range, which can form a narrow beam. This means that the VLC-MIMO system using the transmitted lens can serve multiple users at the same time, which is called the beam division multi-access (BDMA). However, adding a transmitted lens does not significantly change the distribution of LED light intensity.

This MIMO scheme is meaningful for the asymptotic characteristics of large-scale LEDs, and can overcome inter-user interference and realize multi-user communication. On the other hand, due to the use of transmitted lens, the cost is high and the configuration flexibility will be limited.

2) VLC-MIMO precoding

VLC-MIMO precoding could be considered in the view of electrical domain and optical domain. The precoding of electrical domain is consistent with RF-MIMO, thus the commonly used linear precoding can be considered, such as maximum ratio transmission (MRT) precoding, zero-forcing (ZF) precoding, block diagonalization (BD) precoding and singular value decomposition (SVD) based precoding. Due to the impact of the precoding matrix specific value, the precoding signals are difficult to meet the positive value requirement, so it is still necessary to add a DC bias to ensure that the signal is positive on LED. The precoding analysis of optical domain is still researching. Since the signal distribution is no longer Gaussian distributed, it may be necessary to consider the design of nonlinear precoding to approach the channel capacity bound.

Limited by the space diversity gain, the precoding design of VLC-MIMO needs further exploration. Besides, when MIMO is combined with OFDM, the analysis based on the electrical domain is more general, and it is a common idea for precoding design.

## 4.4 Networking Technology

### 4.4.1 Integrated Wireless and Optical Networking

In the cellular network-based RF and visible light heterogeneous fusion networking, it is necessary to research in-depth how to integrate the VLC network of different types, different levels and overlapping coverage and the RF communication network based on the cellular network, and realize the deep coupling of communication, lighting and positioning to form an end-to-end technical system.

1) RF and visible light fusion access

In terms of converged access, it is necessary to consider the process that the RF base station assists the terminal to access the visible light node. One way is that the terminal accesses the RF base station first, the RF base station configures candidate visible light nodes for the terminal, the terminal selects the appropriate visible light node based on the downlink reference signal sent by the visible light node, and reports the RF base station through the RF uplink, and finally the RF base station configures the visible light transmission node for the terminal and perform the visible light downlink transmission. Another way is that the terminal selects one or more suitable visible light nodes by measuring the downlink reference signals sent by the visible light nodes, and initiates a random access request to the RF base station through the RF uplink. At the same time, the selection result is reported to the network, and the RF base station responds and associates one or more visible light nodes for the terminal. In this process, the configuration information of the network to the terminal may be transmitted through the RF downlink or the visible light downlink.

2) RF and visible light fusion transmission

In terms of converged transmission, it is necessary to consider key processes such as RF network-assisted visible light network for HARQ feedback, channel measurement feedback, optical beam switching management, and downlink control signal transmission. For example, the visible light node sends data to the terminal, and the terminal sends ACK feedback to the RF base station through the RF uplink after receiving the data successfully. If the terminal does not receive data or demodulation fails, it sends NACK feedback to the RF base station. After receiving the ACK/NACK information from the terminal, the RF station feeds it back to the visible light node. If the RF base station does not receive the feedback from the terminal within a preset time, it feeds back the NACK information to the visible light node. In addition, considering that VLC technology not only meets the communication needs, but also meets the lighting needs, it is necessary to consider the fusion transmission problem based on dimming.

3) RF and visible light fusion connection management

In terms of mobility management, it is necessary to consider the related technical solutions of the RF base station assisting the terminal to perform visible light downlink multi-connection management. In the RF and visible light fusion networking, the multi-connection technology includes not only the multi-connection between multiple visible light base stations, but also the multi-connection between the visible light base station and the RF base station.

In the RF and visible light fusion connection management based on the cellular network, it is necessary to consider the change of the multi-connection configuration caused by the change of the visible light service node. The movement of the terminal and the change of the environment will lead to the signal strength and service quality of the visible light node to change, thus triggering the switching of the visible light service node. The switch of the downlink transmission function of the visible light node or the RF base station means that the downlink transmission function of the visible light node or the RF base station can be dynamically switched according to the load of the downlink service or the power consumption of the network to optimize the overall transmission performance or power consumption of the network. For example, when the visible light service quality is good, the visible light node can be used for downlink services preferentially for transmission. In this case, more RF resources can be released to support uplink service transmission or provide higher-quality services for users in areas with poor visible light coverage. Therefore, the results of network performance optimization may lead to changes in visible light service nodes. For another example, considering the low power consumption of visible light nodes and the requirement of illumination, the network can comprehensively optimize the network power consumption by considering the overall requirements of lighting power consumption, visible light communication power consumption and RF base station power consumption, and then dynamically switch the downlink transmission of the visible light node or the RF base station to achieve network energy saving. At the same time, the visible light service node may change.

Regardless of the reasons for the multi-connection change, when the terminal selects the visible base station to access and switches the visible base station, if the switch is based on the visible light link, the communication will be interrupted and the terminal cannot access due to the visible occlusion and instability. It is necessary to consider the cellular network-based RF base station assisting the visible light downlink multi-connection management. The terminal reports the measurement report to the RF base station through the RF link. RF base station decides whether the terminal to perform handover and the target base station according to certain decision conditions. The stability of the RF link can ensure the service continuity of the terminal when moving in the network, and improve the efficiency of multi-connection management.

In addition, since the visible light downlink transmission is easy to be blocked and the visible light communication is easily interrupted, the uplink and downlink bidirectional links of RF can assist the rapid recovery of the visible light communication, and provide continuous services for users during the interruption of the visible light communication.

### 4.4.2 Visible light ultra-dense networking

Visible light nodes can be deployed ultra-densely in combination with lighting requirements, but will also bring problems such as frequent switching, low spectral efficiency, and complex interference management. According to the characteristics of visible light channel and network, the user-centered visible light cellular network architecture is considered. By establishing the formation mechanism of amorphous visible light cell and efficient configuration of visible light network resources, the spectral efficiency is improved and the visible light communication from point to point transmission to multi-cell seamless coverage is realized.

- **Amorphous cellular network architecture**

In the future visible light network, the user-centric network architecture allows multiple access points (APs) to simultaneously serve a user and constructs an amorphous cell for each user based on the use's channel quality and interference characteristics, which can realize the most reasonable utilization of space, time, frequency, and user domain resources. The network structure is shown in Figure 4-5. Compared with the 5G network based on RF communication, the VLC network is more conducive to the realization of user-centric network architecture.

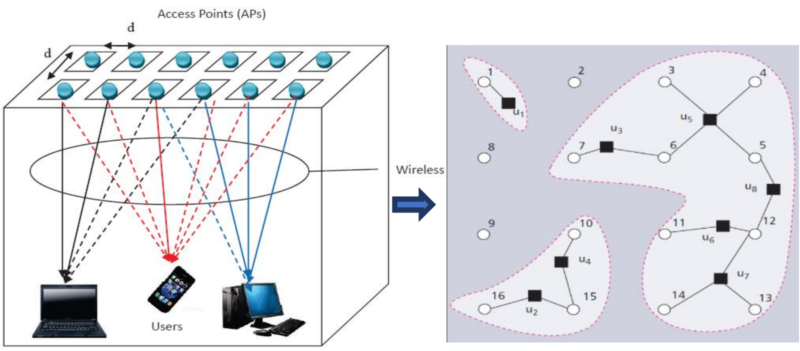


Figure 4-5 User-centric cellular network architecture in multi-light source VLC systems

- **Amorphous cell formation mechanism**

In user-centric visible light cellular networks, scheduling, that is, the pairing between APs and users, is the key to exerting network performance. The matching between users and APs must consider the interference between multiple light sources, the acquisition and interaction of channel state information, and find the best compromise between overall network performance and user fairness. Through an efficient resource scheduling algorithm, a resource allocation scheme with the advantages of low interference, large diversity gain and high user service rate can be selected. In addition, in the ultra-dense visible light deployment architecture, due to the limited modulation bandwidth and illuminance of a single LED lamp, the MIMO transmission method is usually used to meet the communication and lighting requirements at the same time. Optimization issues such as energy efficiency maximization under the constraint of minimum illuminance need to be considered.

# 5. Summary and Prospect

VLC is expected to meet 6G requirements such as area traffic density, user experience data and other important requirements, and improve network performance in peak data rate, network energy efficiency, positioning accuracy and other aspects. However, it also faces considerable challenges in channel modeling, devices, transmission and networking. For channel modeling in different scenarios, there is still a lack of model optimization and application testing for actual working scenarios. In terms of VLC devices, most of the high-performance key devices are still in the stage of laboratory trial production, and there is still a lack of mature industrialized devices, which need industrial pilot test. In terms of transmission and networking technology, it is necessary to combine the characteristics of high-performance visible light devices and visible light channel for targeted design, and form a wireless visible light fusion heterogeneous network together with traditional RF frequency communication (such as medium and low frequency, millimeter wave, terahertz, etc.) to support continuous high rate services in mobile scenarios. In terms of standardization, it is necessary to consider the unification of VLC standards and 6G overall communication standards to maximize the industrial scale of 6G, but also consider the formation of complete VLC device standard system to form an industrial synergy. How to miniaturize and integrate the system is also one of the challenges to be overcome in the industrialization of VLC.

Facing the time of 6G commercialization in 2030, we propose that academia and industry start the overall research on VLC for 6G as soon as possible, plan the direction of industry promotion and standardization research for VLC, and jointly establish and perfect the visible light channel model and complete key device technologies route selection and research, and form key technical frameworks such as transmission and networking. It lays the foundation for the standardization and industrial application of 6G-oriented VLC in the future.

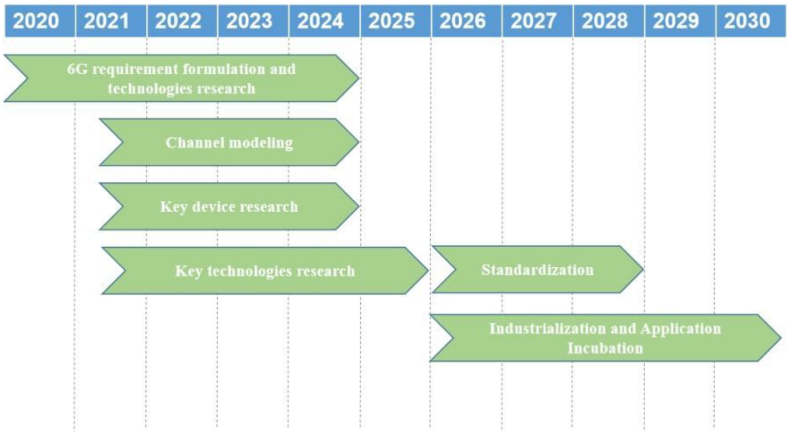


Figure 5-1 6G VLC Technology Research Timeline

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