An investigation on fronthaul and millimeter wave technologies for 5G

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Abstract. The growing demand for communications and the emergence of new applications have put the capacity, transmission rate and latency of communications systems to a more severe test. In this context, 5G communication technology has emerged. 5G applications are divided into three typical application scenarios: eMBB, URLLC and mMTC. In order to support these applications, the key technologies of 5G need to be studied in depth. This paper firstly investigates the networking architecture of 5G bearer networks, and carries out a detailed analysis and comparison of 5G fronthaul technology, including the optical fibre direct connection solution, passive WDM solution, active WDM/OTN solution and WDM-PON solution. Secondly, this paper introduces 5G millimetre wave technology to achieve large capacity and high spectral efficiency transmission, including direct intensity modulation method, external modulation method, optical heterodyne method, optical injection locking method and optical phase-locked loop method. Finally, this paper provides an outlook on 5G fronthaul technology and millimetre wave technology.

1. Introduction

With the rapid development of the Internet, the emergence of new application scenarios has placed higher demands on communication technologies. To support such applications, it is necessary to improve data transmission rates and reliability. In this content, the fifth generation (5G) communication technology is emerged. 5G can support diversity applications, which can be classified into the three scenarios, including enhanced mobile broadband (eMBB), High Reliability Low Latency Connectivity (URLLC) and mMTC [1]. eMBB enables the ultimate person-to-person communication experience through ultra-high data transmission rates. In the coming years, user data traffic will continue to show explosive growth. To increase data rate, 5G achieves a signal bandwidth of 100MHz in the sub6G band and 1Gbps in the millimeter wave band, which is 100 times more energy efficient than 4G. URLLC is mainly used to meet the communication requirements between things, and can support the development of Telematics, Telemedicine, Industrial Control and Autonomous Driving Technology. It can realize a link latency of less than 1ms and support 99.999% reliability in high-speed mobile connectivity. mMTC will rapidly facilitate the deep integration of vertical industries such as smart homes and smart cities through the powerful multi-device connectivity of 5G, and further realize the information interaction between people and things.[2]

Furthermore, the development of 5G research is not only a matter for the communications industry, but will also have far-reaching socio-economic implications. 5G deployment will support long-term sustainable growth in global real GDP, with the global 5G value chain creating $3.5 trillion in output by
2035, while creating 22 million jobs. These figures exceed the value of the entire mobile value chain today. It is clear that "4G is changing lives, 5G is changing society".

During the research of 5G system, many breakthrough key technologies have emerged, among which the fronthaul technology and millimetre wave technology have attracted much attentions. The middle haul and backhaul transmission technologies in 5G bearer networks are relatively mature. The solution for the fronthaul has been studied. In the C-RAN architecture, the fronthaul is defined as the fiber optic transmission network between BBU and RRU. The importance of 5G bearer network construction is evident from the fact that "5G commercial, bearer first" [3]. The popular fronthaul technical solutions can be divided into fiber direct connection solution, passive WDM solution, active WDM solution and WDM-PON solution. In this paper, the principles of these fronthaul schemes are investigated in detail. The current frequency band used for 5G is mainly focused on sub6G, which enables wide coverage and large connectivity. However, the bandwidth of sub6G is limited, so a larger bandwidth millimetre wave band is needed. Millimetre waves are electromagnetic waves between microwaves and light waves, typically at frequencies between 30GHz and 300GHz, which can provide greater signal bandwidth for high rate data transmission. So, it is crucial to investigate wireless transmission solutions over the millimetre wave band. In this paper, five different optical methods to generate millimetre wave are studied.

2. Exploring 5G front transmission bearing solutions

In order to flexibly respond to complex scenarios, the network part introduces the idea of network slicing, which divides the complete physical network into N logical networks, with different networks used to realize different scenarios, thus optimizing resource allocation and improving network efficiency [4]. However, the implementation of network slicing requires the splitting and reorganization of the access network architecture, making the RAN networking approach more flexible. In 5G, the baseband unit BBU in the C-RAN is split into a distribution unit DU and a centralized unit CU. DU is mainly responsible for services with high real-time requirements, CU is mainly responsible for non-real-time services and MEC edge computing functions. Some of the physical layer functions in the BBU are combined with the RRU and antenna to form an active antenna processing unit AAU [5]. The change of access network architecture makes the bearer network structure also changes, which puts forward higher requirements on the bearing capacity of the fronthaul in the bearer network. 4G network uses the fronthaul technology mainly has fiber direct drive and passive WDM. In order to meet the needs of 5G services and the improvement of network architecture, its fronthaul bearer technology also needs further discussion. At present, the main bearer technology in the industry is optical fiber direct connection [6] and WDM technology, WDM according to the different forms of equipment can be divided into passive WDM, active WDM/OTN and WDM-PON [7].

1) Optical fiber direct connection

Figure 1. optical fiber direct connection scheme
The optical fiber direct connection solution does not require any additional transmission equipment, so it is more convenient in the early stage of opening, which is the main advantage of this solution. If a two-fibre bi-directional system is used, each port of the DU and AAU is connected in a point-to-point direct connection. One receiving and one sending requires 6 fibres from each base station to the DU. For an access ring, at least 36 fibres are required from the AAU to the server room, so the two-fibre bi-directional solution consumes a lot of fibres. The 25Gbps BiDi solution was later proposed to address the increased demand for fibre as the number of fronthaul bandwidths and base stations increased. The single-fibre bi-directional optical module BiDi means that the transmitting and receiving wavelengths are transmitted in the same optical fibre, which can save half of the optical cable resources. Even so, this solution is still a significant drain on cable resources and has the disadvantages of unprotected links and poor O&M characteristics.

(2) Passive WDM

![Passive WDM scheme](image)

Depending on the wavelength properties, passive WDM can be divided into passive coarse wavelength division (CWDM) and passive dense wavelength division (DWDM) schemes. But for cost reasons, passive CWDM technology is generally used. This scheme uses WDM technology to achieve the connection between per-DU and AAU. Different wavelengths of light waves are used to transmit different CPRI signals and carry them in the same fibre [8]. Since no active equipment for wavelength conversion is required and only 2 fibres are needed per base station to DU, cost and fibre resources can be effectively saved. As one of the 5G fronthaul solutions, passive WDM is suitable for applications with simple backbone network connections, where service information between adjacent 5G sites can be uplinked to DU sites over a single fibre, but it is not suitable for long distance fibre transmission systems. In addition, it has the following disadvantages. First, due to the high rate of 5G fronthaul, a large dispersion cost (TDP) is incurred when using a passive WDM scheme, so even though CWDM supports 18 wavelengths, it is limited by dispersion and can only utilize the first 6 waves when modulating the optical module. If only 5G fronthaul is considered, a 6-in-1 (1 fibre transmitting 6 wavelengths) model is appropriate. If 4G and 5G stations are co-located, a 12-in-1 model can be used as 4G fronthaul is less affected by dispersion, i.e. the first 6 waves transmit 5G and the last 6 waves transmit 4G. Second, because 5G adopts a C-RAN architecture with CU/DU centralized deployment, then multiple AAUs need to be connected through the fronthaul network, and the DWDM scheme requires different wavelengths for each AAU, so each base station has to plan and manage the wavelengths well in advance. Third the daylighting module required by the scheme lacks an OAM mechanism, which will cause great difficulties for future OAM management [9]. The last point is the complexity of fault location and the limited scalability of the business.

(3) Active WDM/OTN
The solution is configured with WDM/OTN (Optical Transport Network) equipment at AAU sites and DU rooms, allowing multiple forwarding signals to share fibre resources through WDM technology. It supports point-to-point and ring network connections, which is more flexible than passive WDM and requires two fibres per base station to DU, without increasing the consumption of fibres. In addition, AAU and DU devices do not require color light optical modules, avoiding the complexity of wavelength allocation and management by wireless devices. OTN technology can also improve wavelength utilization, provide more comprehensive OAM functions and fault location capabilities. And there is support for delay compensation as a protection mechanism, so it is considered to be a better solution for fronthaul [10]. However, the active OTN solution has higher investment costs and should be chosen according to the specific situation: when the number of AAUs under the DU is small and the distance is close, the simpler optical fiber direct connection solution is used; when the number of AAUs under the DU is large and the distance is long, the passive CWDM or active OTN solution can be chosen.

(4) WDM-PON

The solution is to connect the AAU and optical network unit ONU directly, using the routed WDM technology to communicate each ONU with the optical route terminal OLT PON port through a proprietary wavelength in a point-to-point manner, and the OLT then connects to the DU. With this two-level splitting method, only 1 core of fiber is needed between each base station and DU, which can greatly save fiber resources. In the future, when the number of 5G base stations increases significantly and the pressure on operation and maintenance management increases, WDM-PON or OTN bearing solutions can be used [11].

3. Exploring 5G millimetre wave technology options

Millimetre wave can be generated by optical method and electrical method. Electrical millimetre wave equipment is complex, high production costs and high phase noise, so with the development of
optoelectronic technology, optical millimetre wave technology has become the main means of processing RF signals. Compared with electrical millimetre wave, it has significant advantages in terms of band bandwidth, anti-electromagnetic interference, harmonic range and phase noise. Millimetre waves are electromagnetic waves with a wavelength of 1-10 mm, located in the wavelength range where microwave and far-infrared waves overlap, and therefore feature two wave spectra, corresponding to frequencies of 30-300 GHz. It can be used for different working environments and applications in different contexts, such as radar, remote sensing and strategic communications. According to the different optical technologies that generate millimetre waves, it can be classified as direct intensity modulation method, external modulation method, optical heterodyne method, optical injection locking method, etc.

(1) Direct intensity modulation method

Direct intensity modulation is the simplest and most common modulation method in fibre optic communications, which uses an external modulator to modulate millimetre waves directly onto the optical carrier. A current signal is loaded directly into the laser oscillation and injected into the semiconductor light source, causing the laser oscillation parameters to change, generating high frequency harmonics in the case of oversaturation modulation and filtering out the millimetre wave at the desired frequency [12]. This modulation method has the advantage of being simple and easy to implement, but it also has an unavoidable drawback. When the transmission rate reaches 2.5 Gb/s or more, a chirp phenomenon will occur, that is, the emission wavelength of the laser changes linearly with the modulation current. This results in a broadening of the laser spectrum, which affects the modulation performance and limits the transmission distance of the signal, making it unsuitable for generating high-speed Light millimetre waves. To overcome the chirp phenomenon, external modulation can be used.

(2) External modulation method
External modulation schemes are highly reliable and less costly, and are currently the optimal choice for generating optical millimetre waves. As shown in Figure 6, the external modulation method involves modulating the laser signal and digital signal and outputting it to a combination of an optical modulator (e.g. Mach Zehnder modulator) and filter. Modulating the millimetre wave RF signal to an optical carrier to obtain the modulated signal, which is then transmitted to an optical receiver via optical fibre. The RF signal of the millimetre wave frequency band generated by each sideband and the center frequency beat frequency is demodulated to obtain the transmission information we need [13]. In addition, different modulation schemes can produce millimetre waves in different formats, such as double sideband (DSB) modulation, single sideband (SSB) modulation, and carrier suppression (OCS) modulation.

① DSB modulation can be achieved with different modulators such as dual arm M-Z modulators, phase modulators, electrical absorption modulators etc. The baseband signal is modulated to eventually produce an electrical millimetre wave signal carrying the baseband signal at a frequency of $2\omega_m$. The modulation produces a millimetre wave with high reception sensitivity and high spectral efficiency.

② SSB modulation can be achieved by filtering out one of the side bands in the double-sideband modulation through a filter or grating. It can also be achieved by setting the DC bias of the dual-arm LN-MZM modulator to 1/2 half-wave voltage, but this method requires a modulation frequency equal to the millimeter wave frequency.

③ OCS modulation can be achieved by generating a double-sideband modulation and then filtering out the carrier, or by setting the modulator to suppress the carrier and then using a first-order sideband beat to obtain a millimetre wave. This modulation method requires only half the modulation frequency of the millimetre wave frequency and produces a millimetre wave with high reception sensitivity.

(3) Optical heterodyne method

![Figure 7. Schematic diagram of millimetre wave generation by optical Heterodyne method](image)

The principle of this method is to transmit two narrow linewidth optical waves with a frequency difference equal to the desired millimetre wave frequency, and to load the baseband data to be transmitted onto one of the optical waves. As in Figure 7, two single longitudinal mode lasers output two optical carriers of different frequencies, modulate the data signal onto one of the light waves via a coupler, and finally output a millimetre wave RF signal equal to the frequency difference between the two light waves after tapping the frequency at the receiver [14].

The optical external difference method has many advantages: only one carrier signal with data, so the system has low dispersion. The upper frequency limit of the signal is only limited by the bandwidth of the laser, so it can generate high frequency signals. Two optical carrier beat frequency generated millimetre wave signal intensity, each harmonic component is small, good optical signal-to-noise ratio, etc. However, there are certain drawbacks - the random phase difference between two different frequency light sources causes phase noise. But if a single light source output two light waves at the same time can eliminate phase noise, improve the quality of millimetre wave [15].

(4) Optical Injection Locking (OIL) method
The optical injection locking method can be used to solve the synchronization problem. As the optical carrier in the optical external aberration method is delayed over long distances, causing phase desynchronization between the laser sources and affecting the performance of the system. Injection locking is the injection locking phenomenon produced by the injection of weak signals into a free-running oscillator. This phenomenon is commonly used in electronic and mechanical systems. It can also be achieved in laser systems: a weak, high-performance laser beam can be used to control the spectral characteristics, mode phase and spatial characteristics of the output beam of a strong laser. Light injection locking can be divided into injection locking for continuous lasers and injection locking for pulsed lasers according to the characteristics of the injected light. The locking method is to inject and lock the two slave lasers on two different spectral lines of the master laser to generate two related output light waves, then beat them in the photodetector to obtain the corresponding microwave signal output. Two longitudinal modes with good correlation can be obtained by optical injection locking, so the obtained millimeter wave quality is better, but because the light wave is locked on the ±n-order sideband of the main laser, the phase relationship is constant, so the RF signal bandwidth is affected. However, in order to increase the range of phase lock, an optical phase lock loop method can be used.

(5) Optical Phase Locked Loop (OPLL)

As in Figure 9, the light signals generated by the two lasers are injected into the photodetector, which outputs a beat frequency electrical signal corresponding to the difference in frequency of the light waves of the two lasers. And the resulting signal is fed into a phase detector composed of a low-pass filter and an electrical signal mixer, which outputs an electrical signal related to the potential difference after amplification. And then injects him into one of the lasers to control the injection current, so that the light signals generated by the lasers will change their own phase accordingly. The phase of the laser signal itself will be changed accordingly, and the phase lock between the two optical signals is cyclically achieved. To improve the locking range a laser with a narrower line width can be selected or a shorter loop length can be designed, but the disadvantage of this scheme is that it is difficult to suppress the noisy phase generated by the other laser and is therefore not widely used.
The optical injection phase-locked loop (OIPPL) combines the advantages of OIL and OPLL and, although the system structure is more complex, achieves a low-noise locked phase in the optical range [16].

4. Conclusion
This thesis introduces four 5G fronthaul bearer schemes, namely optical fibre direct connection, passive WDM, active WDM/OTN and WDM-PON, as well as five millimetre wave technology schemes, including direct intensity modulation, external modulation, optical heterodyne, optical injection locking and optical phase-locked loop, and discusses their basic principles, advantages and disadvantages in detail.

The optical fiber direct connection solution is simple to build but consumes too much optical fiber resources. Passive WDM can save optical fiber but has problems such as difficult operation and maintenance management. Active WDM/OTN has the advantages of operation and maintenance management, fault location capability and protection mechanism, and is considered to be the optimal solution for fronthaul. WDM-PON can save a lot of fibre resources and relieve the pressure brought by the increasing number of base stations.

With the quest for higher transmission rates, the technical exploration of millimetre wave band generation methods is becoming increasingly important. Direct intensity modulation is simple and easy to implement, but the transmission distance is limited. External modulation method has the advantages of high stability, low phase noise and low cost, and is the optimal solution for generating millimetre waves. Optical heterodyne method has low dispersion and can generate high frequency signals, but will generate phase noise and delay after a long transmission distance. The optical injection locking method can solve the problem of phase misalignment but its generated signal bandwidth is limited. The optical phase-locked loop method has an extended bandwidth but also produces a certain amount of noisy phase.

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