Analysis and Comparative Study of Mainstream Modulation Methods in Optical Communications

Yutong Yang *

College of Engineering, Yanbian University, Yanji City, Jilin Province, 133002, China

* Corresponding Author Email: 1254023839@ybu.edu.cn

Abstract. Optical communication is the core infrastructure underpinning next-generation information technologies including 5G/6G, cloud computing and big data. As the critical link for electro-optical signal conversion in optical communication systems, modulation technology directly determines the system's transmission rate, capacity and overall cost, and drives the iterative evolution of optical communication systems from 10 Gigabit per second (Gbit/s) to 400 Gbit/s, 800 Gbit/s, and even beyond 1 Terabit per second (Tbit/s). Currently, the optical communication modulation sector features a coexistence of four technical generations. Divergences remain between academia and industry on technical path selection and other core issues, while key bottlenecks like high-order nonlinearity suppression are unbroken, and existing research lacks a systematic review of the field's technological evolution and core contradictions. Taking modulation technology's intergenerational evolution as the main line, this paper sorts out the four generations' core features, analyzes core industry debates, identifies unresolved technical bottlenecks and forecasts development directions. It clarifies the technology's development context and core contradictions, defines breakthrough directions for ultra-high-speed heterogeneous scenarios, and provides systematic reference and theoretical support for related research, engineering application and industrial deployment.

Keywords: Optical communication, Modulation technology, Technology evolution, Performance optimization, Heterogeneous networks.

1. Introduction

As the core link of electro-optical signal conversion in optical communication systems, the performance of modulation technology directly determines the transmission rate, capacity and comprehensive cost, and is also the core support for the evolution of optical communication systems to ultra-1 Tbit/s rates [1].

Since the commercialization of optical communication, modulation technology has iterated to form four generations of technical systems around demand upgrading. At present, the industry presents a pattern of coexistence of multiple generations of technologies. There are still core debates between academia and industry on technical paths and performance optimization, and a number of technical bottlenecks restrict the large-scale application of technologies. Existing studies also lack a systematic review of technological evolution and core industry contradictions [2, 3].

In this context, this paper takes the intergenerational evolution of modulation technology as the main line, systematically sorts out the core characteristics and evolution logic of the four generations of technologies, deeply analyzes the core debates in the industry, clarifies the technical bottlenecks in ultra-high-speed heterogeneous scenarios, and finally predicts the technology development direction, so as to provide support for research and engineering application in this field.

2. The Intergenerational Evolution of Optical Communication Modulation Technology

2.1. Analysis of Evolution

2.1.1. First Generation: Intensity Modulation-Direct Detection (IM-DD) System

This system is the core technology in the early stage of optical communication commercialization. It loads information by changing the intensity of the optical carrier, and the receiving end realizes demodulation through direct detection. The typical representatives are On-Off Keying (OOK), which is the standard for Ethernet below 10 Gbit/s, and 4-level Pulse Amplitude Modulation (PAM4), which is the mainstream for short-reach interconnection within 10 km in 400G/800G data centers [1, 2]. Its core advantages are simple structure, low cost and low power consumption, making it the core subject of technical path debates in short-reach scenarios [2].

2.1.2. Second Generation: Coherent Communication and Phase Modulation System

This system was developed to solve the long-haul transmission bottleneck of IM-DD. It loads information by modifying the phase of the optical carrier, and achieves a qualitative improvement in anti-noise and anti-chromatic dispersion capabilities through coherent detection [1]. It has evolved from Binary Phase Shift Keying (BPSK) and Differential Phase Shift Keying (DPSK) to Quadrature Phase Shift Keying (QPSK) and Differential Quadrature Phase Shift Keying (DQPSK). Among them, QPSK balances spectral efficiency and anti-interference capability, and has become the basic modulation method for 100 Gbit/s long-haul coherent optical communication, as well as the core adaptation foundation for multi-dimensional joint modulation [2, 4].

2.1.3. Third Generation: Multi-dimensional Joint Modulation System

This system is the core technology for 400G/800G ultra-high-speed transmission. It realizes multi-dimensional information loading through the integration of polarization, amplitude and phase, with the typical form of Polarization Division Multiplexing-Quadrature Amplitude Modulation (PDM-QAM) [3]. Among them, PDM-16QAM and PDM-64QAM are the core architectures of current ultra-high-speed systems. Combined with probabilistic shaping technology, they can significantly improve the optical signal-to-noise ratio (OSNR) tolerance, and become the core carrier of debates on performance optimization of ultra-high-speed transmission [2, 5].

2.1.4. Fourth Generation: Flexible Rate and Intelligent Modulation System

This system is a cutting-edge technology adapted to 5G/6G heterogeneous networks. Based on artificial intelligence (AI), machine learning and high-order Digital Signal Processing (DSP) technology, it can adjust the modulation mode and order in real time according to channel conditions and service requirements [6]. Typical forms include Adaptive Modulation and Coding (AMC) and intelligent constellation modulation, which can dynamically balance transmission rate and reliability to adapt to ultra-1 Tbit/s transmission requirements and heterogeneous network scenarios [7]. Currently in the stage of laboratory research and commercial pilot, it is the core research object of engineering implementation challenges [2, 6].

2.2. Comparison of Core Characteristics of Four Generations of Modulation Technologies

Through the analysis of the above four generations of development context, there are significant differences in their core principles, typical formats, core advantages, core disadvantages and core application scenarios, as shown in Table 1.

Table 1. Comparison of core characteristics of four generations of optical communication modulation technologies

Technical System	Core Principle	Typical Format	Core Advantages	Core Disadvantages	Core Application Scenarios
IM-DD	Intensity modulation with direct detection	OOK, PAM4	Simple structure, low cost, low power consumption	Low spectral efficiency, weak anti-chromatic dispersion and anti-noise capability	Short-reach transmission within 10 km, low-cost data center interconnection [2]
Coherent Phase Modulation	Phase modulation with coherent detection	BPSK, QPSK	Strong anti-noise and anti-chromatic dispersion capability, long transmission distance	Upper limit on single-dimensional spectral efficiency	100 Gbit/s long-haul backbone network transmission [4]
Multi-dimensional Joint Modulation	Multi-dimensional modulation combining polarization, amplitude and phase	PDM-16QAM, PDM-64QAM	High spectral efficiency, large transmission capacity	High system complexity, expensive hardware	400G/800G ultra-high-speed long/medium-haul transmission [3]
Intelligent Modulation	Channel-aware adaptive modulation	AMC, intelligent constellation modulation	Dynamic adaptation, balanced rate and reliability	High algorithm complexity, strict real-time requirements	5G/6G heterogeneous networks, ultra-1 Tbit/s transmission scenarios [6]

Overall, the four generations of technologies present an evolution law from single-dimensional to multi-dimensional, from fixed rate to adaptive, and from low-cost short-reach to high-speed long-haul transmission. Each technical system has its adapted application scenarios, forming the current industry pattern of coexistence of multiple generations of technologies.

3. Analysis of Core Debates in the Field of Optical Communication Modulation Technology

The coexistence of multiple generations of modulation technology systems essentially reflects the fundamental trade-offs between "performance and cost" and "rate and reliability". The academic community and industry have formed long-term debates around three core issues [1, 2].

3.1. Analysis of Technical Paths for Short-reach Interconnection Scenarios

In 400G/800G data center short-reach interconnection scenarios, core divergences have formed around the technical selection between PAM4 and coherent modulation. Industry representatives represented by Huawei hold that PAM4 has the advantages of low cost and good compatibility, and can meet the requirements of ultra-short-reach transmission within 10 km when combined with DSP compensation technology, making it the optimal solution for short-reach scenarios [1]. On the other hand, enterprises represented by Cisco argue that as the system rate evolves to 1.6 Tbit/s and 3.2 Tbit/s, the performance shortcomings of PAM4 will gradually become prominent, while coherent modulation has more significant long-term performance advantages, and early layout can reduce the cost of subsequent technology iteration [4]. At present, the industry has reached a consensus on scenario-based differentiation: PAM4 is dominant in ultra-short-reach scenarios within 10 km, while the application proportion of coherent modulation continues to increase in medium-short reach scenarios above 20 km [1].

3.2. Analysis of Performance Optimization Paths for Ultra-high-speed Transmission

In ultra-high-speed transmission scenarios of 400G and above, core divergences have formed between high-order QAM upgrading and multi-modulation multiplexing for performance optimization paths [5]. The academic view represented by Kahn J M holds that increasing the QAM order is the most direct way to improve spectral efficiency, and 256QAM and 1024QAM are the core paths to achieve ultra-1 Tbit/s transmission [8]. Based on Shannon's channel capacity theorem, this approach can fully unlock the capacity limit in high Signal-to-Noise Ratio (SNR) fiber channels [1]. The industry points out that high-order QAM has strict requirements on device and DSP performance, with limited transmission distance, and the scheme combining medium and low-order QAM with polarization and wavelength division multiplexing is easier to implement in engineering [3]. At present, the industry has shown a convergence trend: high-order QAM pilot is promoted in short-reach ultra-high-speed scenarios relying on high SNR advantages, while medium and low-order QAM combined with multi-dimensional modulation and multiplexing is dominant in long-haul ultra-high-speed scenarios, taking into account transmission capacity and distance [3].

3.3. Analysis of Core Driving Forces for Technology Evolution

Around the core driving forces for the development of modulation technology, debates have formed between the academic community and the industry on whether hardware innovation or algorithm optimization should take priority [6].

The academic community holds that the performance breakthrough of core hardware such as lasers and coherent detectors is the core foundation for the iteration of modulation technology, and hardware performance determines the ceiling of algorithm optimization. Every essential breakthrough of optical communication modulation technology from IM-DD to coherent phase modulation, multi-dimensional joint modulation and then to intelligent modulation relies on the performance upgrade of core hardware, and the inherent performance defects of hardware cannot be completely compensated by algorithms.

The industry emphasizes that DSP and AI algorithms can tap the potential of the system without replacing the hardware, and probabilistic shaping and digital nonlinear compensation are typical achievements of algorithm optimization [9]. The "fixed hardware + algorithm optimization" mode is the optimal solution to balance performance improvement and cost control at the current stage [5]. At present, the whole industry has reached a consensus: hardware innovation and algorithm optimization collaboratively drive the evolution of modulation technology, and neither is dispensable [6].

4. Challenges and Development Prospects of Optical Communication Modulation Technology

4.1. Challenges of Optical Communication Modulation Technology

With the evolution of optical communication systems to ultra-1 Tbit/s and the expansion of communication scenarios to 5G/6G heterogeneous networks, modulation technology still faces four core unresolved bottlenecks, which have become the key restricting its large-scale application [6].

First, the challenge of nonlinearity suppression for high-order multi-dimensional modulation. The increase of modulation order makes constellation points denser, and the system's requirements for OSNR and device linearity grow exponentially. The fiber nonlinear effect causes significant damage to high-order signals, while the current mainstream compensation algorithms are mostly built based on linear models, with limited suppression effect on nonlinear distortion [6, 10].

Second, the engineering implementation barrier of intelligent modulation technology. The AI algorithms relied on by intelligent modulation have huge computing power requirements, and existing commercial DSP chips cannot meet the real-time processing requirements of ultra-high-speed systems, with insufficient algorithm generalization ability. Meanwhile, real-time channel state detection and dynamic adjustment of modulation parameters have extremely high requirements for the system feedback mechanism and control accuracy, and the existing architecture can hardly balance real-time performance and precision [6].

Third, the cost and energy consumption optimization bottleneck for full-scenario adaptation. The supporting DSP chips and coherent detection devices for high-order multi-dimensional modulation and intelligent modulation are expensive, restricting their application in low and medium rate short-reach scenarios. Meanwhile, the energy consumption of DSP processing and coherent detection links related to modulation accounts for a very high proportion, and existing technologies can hardly achieve the collaborative optimization of performance improvement and energy consumption reduction [1].

Fourth, the lack of standardization and compatibility in heterogeneous networks. At present, there is no unified industry standard for the signal format and core parameters of modulation technology, and the interfaces and processing logic of systems from different manufacturers are incompatible, leading to obstacles in signal interaction in heterogeneous networks. Meanwhile, a single modulation technology can hardly adapt to the complex and changeable channel conditions of heterogeneous networks, and there is still no mature scheme for cross-scenario adaptive switching [3].

4.2. Development Prospects of Optical Communication Modulation Technology

In the future, optical communication modulation technology will develop towards four core directions: intelligent adaptation, low cost and low energy consumption, multi-dimensional integration, and standardization and compatibility. It will be promoted collaboratively from three dimensions of technical research, engineering application and industrial development, and finally realize the implementation of ultra-1 Tbit/s transmission and adaptation to full-scenario heterogeneous networks [6].

At the technical research level, the in-depth integration of AI algorithms and modulation technology will be promoted, the nonlinear compensation model will be optimized through deep learning and machine learning, and the bottleneck of nonlinear distortion suppression for high-order multi-dimensional modulation will be broken through [11]. Meanwhile, the combination of high-order QAM and probabilistic shaping technology will be advanced, to improve spectral efficiency while optimizing OSNR tolerance, and balance the performance and reliability of ultra-high-speed transmission [6].

At the engineering application level, scenario-based customization will be deepened, the applicable technical boundaries of different modulation systems will be further clarified. For different scenarios such as short-reach ultra-high-speed, medium and long-haul transmission, and 5G/6G heterogeneous networks, the advantages of the four generations of modulation technologies will be customized and integrated to achieve scenario-based complementarity and efficient collaboration, and balance the performance, cost and practicability of engineering implementation [3].

At the industrial development level, the construction of industry standards for modulation technology will be accelerated, the signal format, core parameters and equipment interfaces of heterogeneous networks will be unified to solve the compatibility problem between manufacturers. Meanwhile, taking the collaborative innovation of software and hardware as the core driving force, the performance bottleneck of core hardware will be broken through on the one hand, and DSP and AI algorithms will be continuously optimized to tap the potential of existing hardware on the other hand. The two paths will jointly promote the evolution of modulation technology to ultra-1 Tbit/s transmission, and realize the collaborative optimization of cost and energy consumption [6].

5. Conclusion

This paper sorts out the core characteristics and evolution logic of four generations of modulation technologies in the optical communication field: IM-DD, coherent phase modulation, multi-dimensional joint modulation, and intelligent modulation. It analyzes the core debates between academia and industry on three aspects: technical path for short-reach interconnection, performance optimization for ultra-high-speed transmission, and core driving forces for technology evolution, and identifies four major unresolved technical bottlenecks. The evolution of optical communication modulation technology has always revolved around the core contradictions between performance and cost, rate and reliability, and the industry has formed a development consensus of scenario-based adaptation and collaborative innovation of software and hardware.

In the future, modulation technology will take intelligent adaptation, low cost and low energy consumption, multi-dimensional integration, and standardization and compatibility as the core development directions, break through existing technical bottlenecks, and provide core support for the development of high-speed and large-capacity optical communication systems.

References

[1] Li Z, Chen X, Li G, et al. Advances in high-speed optical modulation technologies for 800G/1.6T optical communication systems. IEEE Journal of Selected Topics in Quantum Electronics, 2023, 29: 7300415.

[2] Tan M, Gao Y, Fu S, et al. Evolution and prospect of optical modulation formats for data center interconnection. Chinese Optics Letters, 2023, 21 (4): 040602.

[3] Rios-Müller R, Renaudier J, Charlet G. PDM-QAM for ultra-high-speed long-haul optical transmission: advances and challenges. IEEE Photonics Technology Letters, 2022, 34 (19): 1023–1026.

[4] Che D, Al Amin A, Shieh W. Short-reach coherent optical communications for 1.6T/3.2T data center interconnects. Journal of Lightwave Technology, 2022, 40 (18): 5892–5904.

[5] Fehenberger T, Bisplinghoff A, Spinnler B. Probabilistic shaping for high-order QAM in ultra-high-speed optical systems. IEEE Transactions on Communications, 2022, 70 (8): 5212–5225.

[6] Zhang Y, Wang K, Zhang J, et al. Machine learning-enabled adaptive modulation for 6G optical communication networks. IEEE Internet of Things Journal, 2023, 10 (13): 11234–11245.

[7] Chen H, Li L, Li G. Adaptive modulation and coding for 6G heterogeneous optical access networks. In: Proceedings of the Optical Fiber Communication Conference (OFC), San Diego, CA, USA, 2023: Th3B.4.

[8] Zhang F, Han Y, Yu C. Hardware-efficient DSP algorithms for coherent optical receivers in 800G/1.6T systems. IEEE Transactions on Circuits and Systems I, 2023, 70 (3): 1245–1258.

[9] Mazur M, Schröder J, Karlsson M. Advanced modulation formats for beyond 1 Tbit/s per channel optical transmission. Journal of Lightwave Technology, 2023, 41 (10): 2456–2468.

[10] Zhou X, Cai Y, Chandrasekhar S. Machine learning for optical communication system optimization: advances and challenges. Proceedings of the IEEE, 2023, 111 (10): 1371–1392.

[11] Liu S, Dong Z, Yi X. Digital nonlinear compensation for high-order QAM coherent optical systems. Optics Express, 2022, 30 (11): 18765–18778.