Spectrum analysis of multi-pulse position modulation in optical communication

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Abstract. In this paper, the authors aim to compare the performance of space optical communication and wireless optical communication by analyzing the transmission mechanism, transmission method, and transmission rate of MPPM (Multi-Pulse Pulse Position Modulation). MPPM is a widely used modulation technique in optical communication systems, which has the advantage of reducing the effect of noise and improving the system's error rate. To achieve the objective, the authors will employ mathematical models to compare the performance of space optical communication and wireless optical communication. They will analyze the transmission mechanism, transmission method, and transmission rate of MPPM in both communication systems and draw conclusions based on their findings. The authors hope that the results of this study will positively promote the development of MPPM in the future. By comparing the performance of space optical communication and wireless optical communication, this study will provide insights into the strengths and weaknesses of both systems, which can help in the development of more efficient and reliable optical communication systems.

Keywords: PPM, OOK, FSO, QAM-MPPM, PCR, PMT, APD.

1. Introduction

A signal modulation method known as Pulse Position Modulation (PPM) is used in wireless communication to convert digital signals into a sequence of pulses. This method uses a reference signal to cause the position of each pulse in the signal to vary instantaneously according to the sampling ratio of the message or modulation signal. If there is a signal with M bits, this method transmits the data of these M bits by sending a pulse, which can have 2M different possibilities, and repeats with a specific period "T"[1][2].

Applying the principles of water to time signals, Aeneas Stymphalus invented the Greek hydraulic signal system in 350 BC, which is recognized as the earliest recorded instance of pulse position modulation (PPM). The origin of modern pulse position modulation can be traced back to 1853 with telegraph time-division multiplexing, and it developed along with pulse-code modulation and pulse-width modulation. In the early 1950s, PPM was used for radar signal processing and to improve radar system performance. By the late 1950s, PPM began to be used in digital communications, and this method performed well at low signal-to-noise ratios. With the development of wireless communication technology, PPM technology has been further improved and optimized to enhance the performance and fault tolerance of wireless communication systems. However, traditional PPM technology can only transmit a single pulse within the same symbol time, which limits the transmission rate and fault tolerance. Therefore, multi-pulse position modulation (MPPM) has been proposed as a new digital modulation technology, which is constantly being improved and optimized.

MPPM modulation is a method of mapping n-bit binary digits into PPM symbols composed of M information slots according to certain rules. In each PPM symbol of MPPM modulation, there are at least two slots with signal light pulses, denoted by 'a', while no signal light pulse is present in other slots. From the structure of MPPM modulation, it can see that the symbols are not completely orthogonal to each other, and the number of symbol types is not necessarily a power of 2. Therefore, the problem of redundant constellation points exists in MPPM modulation. The number and position

of the redundant constellation points in MPPM will directly affect the performance of the communication system[3].The current research focus of MPPM technology is concentrated on several aspects. The first one is the improvement of fiber optic transmission performance. MPPM technology is widely used in fiber optic communication, but there are issues such as background noise in fiber optic transmission. To suppress background noise, techniques such as spatial filtering and signal modulation are generally used. In several research areas, Multi-Pulse Position Modulation (MPPM) is currently a topic of great interest. The first is improving the performance of optical fiber transmission. MPPM is widely used in optical fiber communication, but there are issues with background noise. To suppress background noise, spatial filtering, and signal modulation techniques are generally used. When designing a filter, various factors must be taken into account, such as the arrival angle of the signal, Doppler frequency shift, laser linewidth, and the number of time patterns. Multi-pulse position modulation is one of the most commonly used background noise suppression modulation techniques [4]. The second is hybrid MPPM, which combines MPPM technology with other digital modulation techniques to further improve system performance and fault tolerance. Khallaf et al. [5] applied a modulation method that mixes orthogonal amplitude modulation with MPPM to the turbulence-free and gamma-gamma-free space optical (FSO) channel. This hybrid modulation method achieved better bit error rate performance than traditional modulation methods. Elfiqi et al. [6] proposed a hybrid two-level MPPM-multi-decimal phase shift keying(2L-MPPM-MDPSK) technology, which achieved higher power and spectral efficiency. Numata et al. [7] proposed a scheme that combines multi-pulse position modulation with pulse interval modulation (PSM). Bit error rate analysis was performed in a simulated noise scenario, and high-speed transmission was verified. Two modulation schemes, namely inverted pulse position modulation and subcarrier inverted pulse position modulation, were proposed by Hidemitsu Sugiyama et al. These two modulation schemes can provide superior LED brightness for visible light communication, indicating that subcarrier modulation can suppress the effects of background light[8]. The hybrid MPPM techniques provided in the above articles provide new ideas and combinations for the development of new mathematical models related to MPPM. This article provides a mathematical model that will be compared with the above hybrid MPPM mathematical model and discusses the rationality and characteristics of the proposed mathematical model.

This article focuses on analyzing specific performance cases of spatial optical communication and wireless optical communication, comparing the mathematical model with previous models and exploring the changes in performance. The author focuses on the spectral analysis of MPPM modulation in optical communication and conducts simulation analysis on performance parameters such as transmission rate, transmission bandwidth, transmission power, and error symbol rate. Following a logical structure, the article studies the modulation and demodulation technology of MPPM in optical communication and verifies the feasibility of optimizing the MPPM modulation scheme through simulation analysis using MATLAB software. In addition, MPPM research can be applied to mixed modulation technologies with higher transmission rates and more complex demodulation techniques in the field of optical fiber communication, such as BPSK-MPPM [9], QAM-MPPM[10], and DPSK-MPPM [11].

2. Theoretical analysis of mppm

The wireless optical communication system model mainly includes three modules: transmitter, atmospheric channel, and receiver. The transmitting end converts digital information into a laser and emits it from the transmitting source. Optical signals pass through atmospheric channels. The optical antenna at the receiving end can receive optical signals and transmit the identified signals to the photodetector. After being processed, the digital signals can be restored. In its principle, the signal source is the source of electrical signals, and the signals are mostly discrete digital signals; The sink restores the source to a specific signal, which is the destination of signal transmission. A complete communication system is characterized by a source and a sink. The coding of the source samples

continuous analog signals into discrete digital signals or compresses digital signals to improve transmission efficiency. The decoding of a source is an inverse operation of the encoding. Channel coding adds periodic fixed codes with protection functions to source coding to counter channel interference and reduce the impact of noise. The decoding of the channel interprets the signal according to rules that are inverse to the transmitter and removes errors generated during transmission[12].

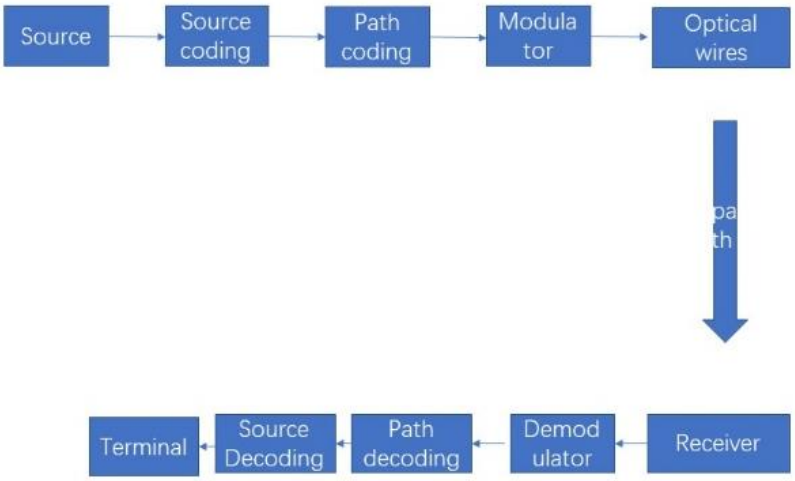


Fig 1. Process of the light communication

Satellite optical communication is an efficient communication method, and its research focuses on power utilization, frequency band utilization, and information transmission efficiency. PPM is an orthogonal modulation method in satellite optical communication, in which the nominal position moves linearly with the sampled value of the information signal, and MPPM is an improvement on it. The optical transmitter maps information into MPPM frames and transmits data according to an accurate clock; After receiving the optical signal, the receiver determines the nominal position based on clock synchronization and restores the signal. In MPPM, the main factor affecting the accuracy of information is time slot asynchrony, which is caused by the influence of noise and pulse broadening in Poisson channels on the number of photons in the correct time slot [13].

Wireless optical communication is a commonly used communication technology. Outdoor wireless optical communication is mainly affected by atmospheric channel characteristics, leading to performance degradation. MIMO (Multiple Input Multiple Output) technology can reduce the optical intensity bullying of signals received at different locations by randomly distributing their attenuation, thereby reducing the attenuation caused by atmospheric influences in wireless optical communication during transmission. By further combining NIMO technology with ultra-Nyquist rate wireless optical communication technology, the impact of atmospheric turbulence can be further reduced at high frequency spectral efficiency [14].

Visible light communication technology has developed rapidly in modern times. A more mature implementation method is to design according to the infrared communication channel link aversion and divide the distance between the transmitter and the receiver into line-of-sight transmission links, scattered transmission links, and quasi scattered transmission links. Based on strict optical alignment, the field of view angle of the photodetector can be adjusted small enough to reduce the impact of noisy light sources. On this basis, using diversity multiplexing technology can significantly increase transmission speed. In practical applications, due to the vulnerability of the line-of-sight transmission chain to obstacles, this technology is often applied to short-range indoor optical communication technology with high performance-to-noise ratio [15].

3. Results

3.1. Space optical communication

An optical communication system that employs laser light waves as the carrier wave and utilizes the atmosphere as the transmission medium is known as Free-space optical communication(FSO). The field of space laser communication has made significant progress due to the high-speed transmission and large communication capacity provided by free space laser communication, which combines the advantages of optical fiber communication and microwave communication while avoiding the need to lay optical fiber. Consequently, considerable manpower and material resources have been invested in this technology. This chapter mainly introduces a case analysis of QAM-MPPM in a turbulence-free FSO channel.

The utilization of index-modulation (IM) technology in optical communications has spurred the development of several novel waveform schemes, which endeavor to impart higher-density information through the manipulation of distinct signal characteristics [16]. One of the recommendations is a mix of MPPM and quadrature amplitude modulation (QAM). This instance suggests a novel demodulation technique, providing an accurate analytical expression of the error probability for non-turbulent FSO channels in the case of conventional and novel detectors. Simplified expressions for estimating the probability of error are provided in the case as well. The results of this study demonstrate a 0.1 dB increase in signal-to-noise ratio (SNR) for the new detector compared to the previously defined detector, along with more precise error probability estimation when compared to previously published results.

As an information source, this case considers an equal-probability binary information source that generates an independent, identically distributed bit sequence to power the QAM-MPPM modulator. The signal frame period is divided into slots of equal duration, $T_s = T/N$, by the modulator. Only $1 \leq w \leq N$ slots will take actions during each frame period, following the MPPM pattern[17][18].

In accordance with [19], a QAM symbol is inserted in each signal slot. QAM symbols have MQ elements, and by definition, the number of information bits for each QAM-MPPM symbol can be defined.

MQ≥4 has been considered in this case, square QAM constellations are even nQ, and odd trans-QAM constellations nQ (The only exception to this rule is when $n_Q = 3$, in which case the shape is rectangular). Gray coding and energy-normalized QAM constellations are also taken into consideration in this case. In order to prevent clipping, it is recommended to set the modulation index value **m** to **S**(T)≥0 in the following case. Upon traversing the turbulence-free FSO channel, The received current waveform is generated by the photodiode (PD) due to the light intensity fluctuations produced by the light source. In the case of turbulent FSO channels, the optical channel gain is constant, so it will be treated as a constant value from now on. In this case, no dispersion in the optical channel is considered. The calculation enables the average received optical power to be obtained. Assuming an energetically normalized QAM constellation, the average energy of the received QAM symbol within a signal slot can be expressed. In this case, the noise **z**(t) is modeled using a standard construction as proposed in [20, 21].

One potential demodulation approach is to follow the suggestions presented in [21], as discussed in this case. For each time period, **k**=0,..., N−1, the I/Q detection value is calculated using the known principle of the QAM correlator detector in the signal space frame. The MPPM symbol section uses metric detection. Sort **x**k based on the maximum likelihood (ML) rule. The utilization of indicators is proposed as a means of detecting the MPPM symbol in the second alternative approach. A receiver based on a matching filter detector is applied to a rectangular pulse shape and, according to the ML rules already mentioned, detects the signal slot by ordering these values.

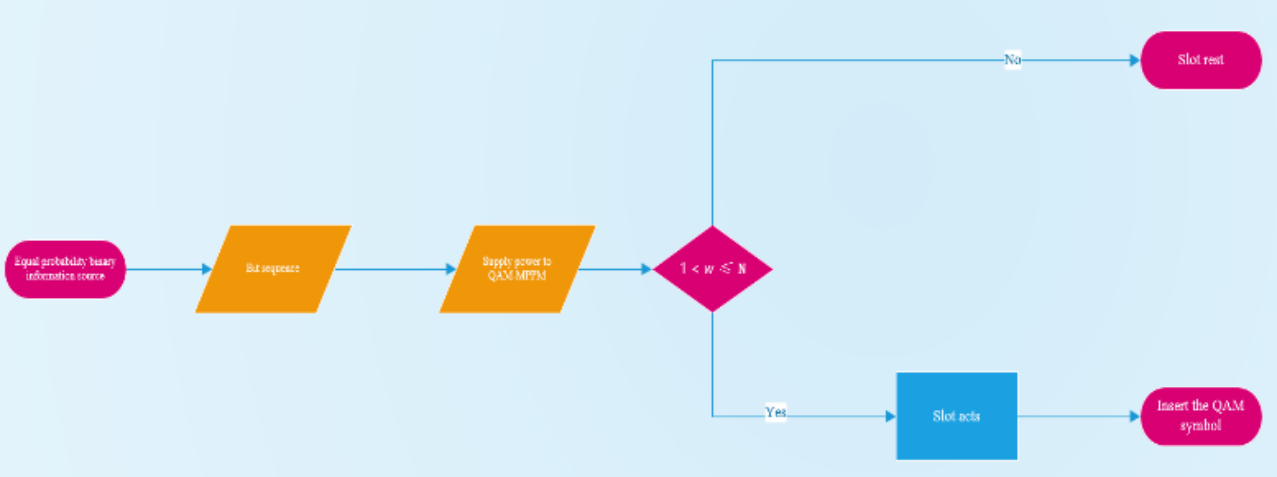


Fig 2. A flowchart from Case One

This scheme proposes a new method for demodulating the indexed modulated waveform for optical channels that has been proposed, called QAM-MPPM. This methodology provides analytical formulations for the calculation of mean symbol and bit error probabilities within AWGN channels, encompassing novel probes in addition to those already published [19]. Analytical expressions, as well as practical techniques, are suggested in this scheme for computing the statistical metrics of mean sign and bit error probabilities, and simulations show that the recommendations of this scheme are suitable for both detectors. The scheme also verifies the following one-sixth dB gain E_b/N_0 at little additional cost when applying the new demodulation method. This is a clear advantage.

In addition to using simulation results to validate the scheme's approach, the formula previously published in [19] was used for QAM-MPPM to evaluate its relative accuracy. The present scheme represents the pioneering attempt to deliver an analysis of QAM-MPPM.

3.2. Wireless optical communication

Utilizing optical carriers for information transmission, wireless optical communication presents a viable communication approach boasting high transmission rates, immunity to electromagnetic interference, and remarkable reliability. With potential applications ranging from "last mile" problem resolutions to emergency and satellite communications, this technology bears substantial promise. One promising solution for short-range wireless communication lies in the form of ultraviolet communication (UVC) technology, which has garnered substantial attention owing to its wavelength range of 200 to 280 nm. This section focuses on a case study of multi-pulse pulse position modulation in non-open distance UV communication applications. Regarding PMT and APD, the amplification process they employ transforms detected photons into an electric current, whereby the resulting gain follows a Gaussian distribution with a random nature.

To examine the performance of MPPM with respect to SER and ADR under NLOS UVC, the discrete memoryless channel model serves as a basis, whereby the channel is described using the probability transfer matrix **H**. It is assumed that the transmitted symbols are evenly distributed on **x**. In the discrete memoryless channel model, the probability transfer matrix **H**, where **H**i,j denotes the element in row i and column j, corresponds to the conditional probability of receiving zi upon transmission of **x**j, expressed as Pr(**z**i |**x**j). The value of **H**i,j is dependent on the number of MPPM symbol slots that are identified incorrectly.

Under this scenario, the MPPM's UV light source generates an optical signal, which subsequently scatters off atmospheric particles within the channel before arriving at the detector. In the MPPM symbol, there are M slots, N of which constitute pulse slots. The mean count of detected photons in the pulse and empty slots are represented by λp- and λu-, correspondingly. Following the SDD scheme, the top N slots in terms of their counts within the PED output signal are selected as pulse time slots within the MPPM symbol. The performance of MPPM with respect to SER and ADR under NLOS

UVC is analyzed through the use of a probabilistic transition matrix, and the channel can be described by adopting a discrete memoryless channel model.

The Poisson distribution can be used to model the output signal of PCR, and a random selection of slots from the draw will be treated as pulse slots according to SDD. In the context of assessing ADR, an MPPM symbol's information content is assessed via the utilization of the mutual information of the NLOS UVC channel as a quantitative measure. As such, it is employed for quantification purposes. To ensure a fair comparison of MPPM ADR performance across different total time slots, normalization of the total time slot **M** is employed. For PMT and APD, the output signal can be described in terms of PTG distribution.

This case study presents and analyzes the SER, **pw**(w), and ADR results of MPPM in an NLOS UVVC system. The results of the analysis on SER and **pw**(w) for PCR, PMT and APD exhibit excellent consistency with the corresponding Monte Carlo simulation outcomes. Furthermore, the upper bound for pt approaches the analysis results progressively as it increases, particularly in the case of SER. As a result, the proposed upper bound equation is capable of achieving the analysis results of high average optical transmission power. Notably, MPPM using PCR demonstrates the best SER performance. Analytical formulations for the SER and ADR of MPPM within NLOS UVC systems are developed in this study, under the condition that the detector's output signal is subject to Poisson and PTG distributions. Additionally, an upper bound formula for the detector output signal is derived, which is valid for the PTG-distributed MPPM within the passive ultraviolet light system. The theoretical findings are corroborated through Monte Carlo simulations. The case uses three typical detectors, including PCR, PMT, and APD.

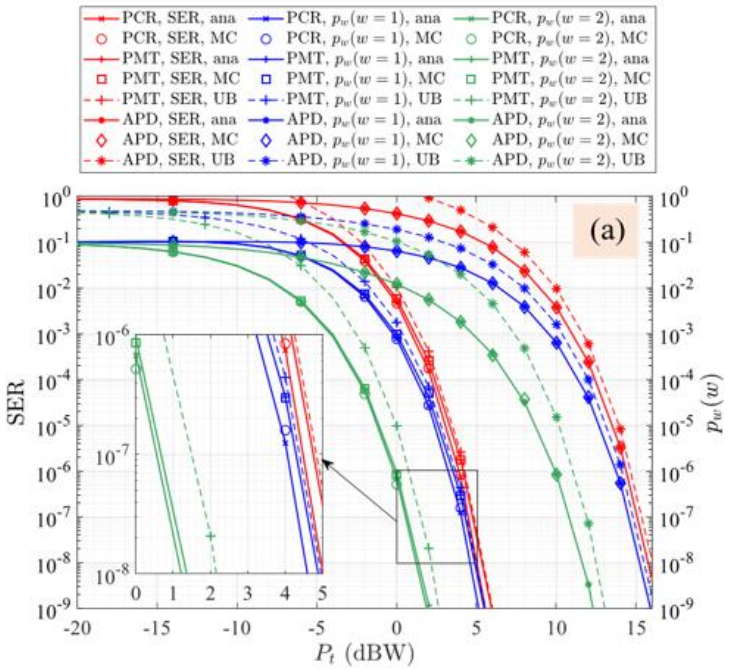


Fig 3. The SER and ***pw***(*w*) outcomes for MPPM within NLOS UVC systems are reported as a function of the average optical transmission power (**P***t*). [14].

The practical efficiency of PMT and its usefulness for designing optical communication systems based on MPPM with PEDs is shown in Fig. 3. Given that MPPM is a time-domain exponential modulation, the findings presented in this research hold relevance for the design of NLOS UVC systems that employ exponential modulation.

Satellite optical communications

There are some technical intersections between signal modulation and demodulation technology and background noise suppression technology, and the specific modulation and demodulation technology can also achieve suppression of signal background noise.

The basic free space optical communication system is shown in Fig. 4.

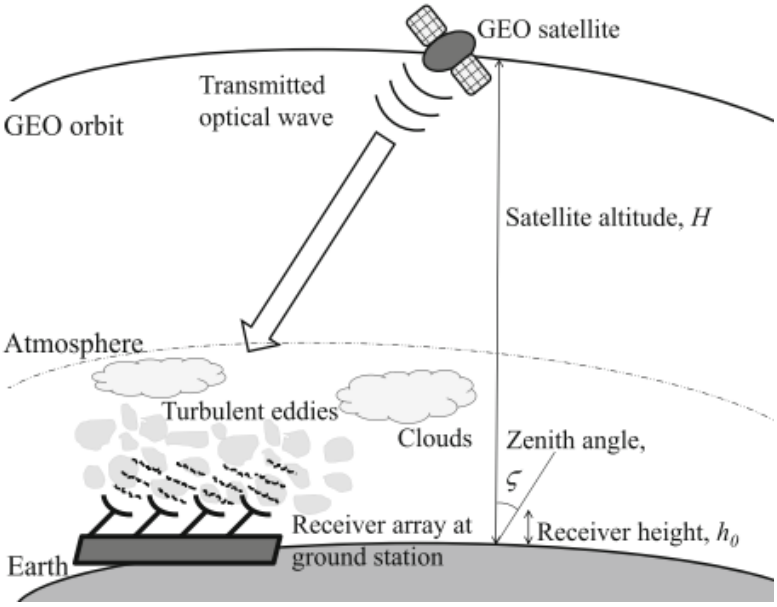


Fig 4. A schematic illustration is presented to depict the fundamental block diagram of a free space optical downlink that transmits signals from a satellite located at an altitude **H** to a ground station positioned at a height of *h*0 above the ground level with a specific zenith angle ς [23]

Signal modem and demodulation techniques are selected based on optical power efficiency and bandwidth efficiency, information transmission rate, and anti-interference capability. Multiple binary and multi-level modulation formats can be supported by modulation schemes used in satellite optical communications, with binary being the most prevalent format due to its simplicity and efficiency. Within binary systems, on-off keying (OOK) and *PPM* are the two most commonly used modulation methods. Due to their simple characteristics, OOK modulation schemes have become one of the mainstream technologies for satellite optical communications and are usually deployed synchronously with intensity modulation/direct detection (IM/DD) transmission and reception mechanisms. Literature [9] adopts different intensity modulation schemes to attenuate the influence of atmospheric turbulence on the signal and analyze its effects. Based on Fig. 5, it can be observed that the optimal performance in mitigating turbulence effects is achieved by the adaptive threshold technique for OOK modulation.

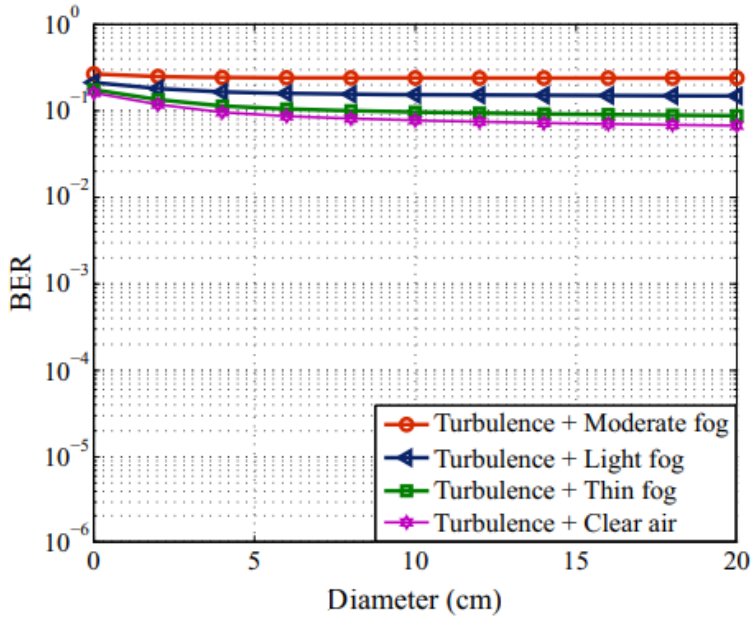


Fig 5. Bit error rate (BER) versus aperture diameter for OOK scheme [23]

The Table.1 below is the full comparison of BER of OOK and MPPM in different conditions.

Table 1. Average Received Power (Dbm) For A Ber[23]

IM scheme	Weather conditions	Required average received power (dBm) for a BER of 10^{-6}			
		Point receiver		Finite aperture receiver	
		$D = 1$ cm $R = 1$ no.	$D = 16$ cm $R = 1$ no.	$D = 8$ cm $R = 4$ nos.	$D = 4$ cm $R = 16$ nos.
OOK	Turbulence + Moderate fog	−8.35	−24.60	−25.38	−26.02
	Turbulence + Light fog	−10.26	−26.34	−27.12	−27.76
	Turbulence + Thin fog	−11.55	−27.55	−28.32	−28.97
	Turbulence + Clear air	−12.04	−28.01	−28.79	−29.43
64-DPPM	Turbulence + Moderate fog	−16.08	−33.02	−33.80	−34.45
	Turbulence + Light fog	−18.22	−34.77	−35.55	−36.19
	Turbulence + Thin fog	−19.63	−35.98	−36.76	−37.40
	Turbulence + Clear air	−20.16	−36.44	−37.22	−37.86
64-PPM	Turbulence + Moderate fog	−17.09	−34.48	−35.27	−35.91
	Turbulence + Light fog	−19.37	−36.24	−37.01	−37.65
	Turbulence + Thin fog	−20.85	−37.45	−38.23	−38.87
	Turbulence + Clear air	−21.41	−37.91	−38.69	−39.33

Compared with wireless optical communication, satellite optical communication has a series of advantages such as large channel capacity, low power consumption, light weight, and high confidentiality. However, it also has inevitable defects, such as space targeting, capture and tracking of satellite optical links, which are still difficult for current technology; In addition to this, there are some effects of the presence of background light. At the same time, there is also relative movement between terminals, and the long communication distance between satellites will greatly reduce the sensitivity of satellite optical communication.

Satellite optical communication is developing towards two-way transmission, point-to-multipoint transmission and networking. In order to build a satellite industry network that integrates space, space, and ocean, business data needs to be transmitted back to the earth's surface. In this process, it is done between satellites. Data relay transmission is an essential link. Satellite two-way transmission satellite communication network terminals can transmit information and data more efficiently. Transmission and receive rates can be guaranteed. Because the divergence angle of the laser beam is very small

But there is also motivation. Currently, point-to-point transmission is the dominant mode in satellite optical communication links. In order to extend the satellite network, the implementation of multipoint-to-point technology is necessary.

3.3. Comparison

1. Comparison of service carrying capacity. PDH can meet the performance requirements of various service bearer transmissions and has high service carrying capacity. SDH is a bearer technology that is relatively suitable for tap multiplexed services in actual services, but it cannot solve the problem of video signals and non-real-time services in real-time services

Ethernet transmission problems in services require the use of access devices when transmitting narrowband services. Generally, only point-to-point communication channels are provided, and it is difficult to meet the requirements for a large number of collinear communication channels: MSTP has good service carrying capacity and scheduling capabilities, which can improve the speed of its network and reduce costs; Each link of DWDM has its own service carrying capacity. The device service interface is relatively rich and the configuration is relatively flexible. CTN adopts TDM system multiplexing technology. The fixed bits in the occupied time of each channel signal are grouped, and after grouping, they can be divided into different rate levels to realize integrated service transmission from narrow to broadband. The equipment is relatively simple, the networking is relatively flexible, and centralized maintenance is relatively convenient, and no need for any access devices can support voice, etc.; ASON has extensive network scalability, relatively flexible services, and can also improve value-added services and fast services.

2. Comparison of maturity and development prospects. PDH technology is relatively mature and has certain market prospects; SDH technology is relatively mature, and MSTP has a wide application base: high convergence scheduling, strong comprehensive carrying capacity, good survivability, and can ensure broadband operation, so as to realize the fast and convenient establishment of services and meet the market demand for subway transmission network DWDM, as the mainstream long-distance transmission technology, has high technology maturity and good development prospects; 0TN has been widely used in the field of rail transit at home and abroad. TN, as a patented technology of Siemens, is relatively mature.

In terms of demand, it can provide R&D and updating, and the development speed is relatively fast; ASON was born with the need for network management and reduced operating costs, and gradually matured with good development scenarios.

Table 2. Comparison Between Space Light And Wireless Light

	Space light	Wireless light
Propagation medium	Optical fiber	Air
Security	Good with security	Strong anti-interference capability
Communication rate	High	Relatively high
Propagation speed	High	Extremely high bandwidth
Band selection contrast	Convenient band selection and large information capacity	No need to choose band
Cost	High	Relatively low
Volume	Large	Small

4. Conclusions

By discussing the case study of MPPM in different states of optical communication, this paper focuses on comparing the characteristics of communication rate and propagation speed and compares different communication methods from the perspective of industry, and finally obtains the table shown in Table 1. The author analyzes the performance conversion of optical fiber communication, which is one of the hot issues of MPPM and has a positive role in promoting the development of MPPM in the future.

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