

Design of a pulse amplitude modulation-based communication system

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Abstract. The paper presented aims to introduce readers to communication systems that utilize pulse amplitude modulation (PAM) as a means of transmitting data. PAM is a form of modulation that involves varying the amplitude of a series of pulses to represent the information being transmitted. The paper provides a detailed analysis and comparison of various PAM-based communication systems, highlighting their strengths and weaknesses. The main objective of the paper is to offer insights into the design of PAM-based communication systems. By thoroughly examining the different PAM-based communication systems, the authors aim to provide readers with a general understanding of the key considerations involved in designing such systems. The paper concludes with a summary of the main findings and offers some general guidelines that can be applied when designing PAM-based communication systems. Overall, the paper offers a valuable contribution to the field of communication systems, particularly for those looking to design systems that use PAM as their modulation scheme. The insights and guidelines provided in the paper are of reference significance and can be used to inform the design of future PAM-based communication systems.

Keywords: PAM, communication system, visible light communication, PAM4.

1. Introduction

PAM modulation is a type of pulse modulation, which is a linear amplitude modulation. In the PAM modulation process, the pulse height signal varies with the original signal, and the modulated signal can visually reflect the waveform of the original signal, its principle is simple to understand and not complicated to implement. Because of these features, PAM modulation was soon applied to the design of communication systems after it was first proposed, and PAM has since been widely used and still plays an important role today.

At this stage, the use of PAM-based systems has become more proficient and is not only used in the field of communication. On the one hand, scientists are continuously developing the use of PAM-related knowledge based on the various components of the communication system, improving the individual modules' performance, that is, the receiver and transmitter sections. At the same time, scientists have optimized and improved PAM-based communication systems as a whole, using them in specific scenarios that have led to their playing an important role in many areas, such as in the field of communication, where PAM is often used in Ethernet long-range transmission [1] and in optical communication [2]. In photobiological systems, where PAM is often used to quantify the amount of certain substances. In microcontrollers and some circuits, PAM is used to generate some control signals [3].

At the same time, with the development of fiber optic communication, PAM has been used more and more, and improvements have been made, from dimming schemes that adjust the probability and intensity of PAM constellation points, to further VLC hybrid dimming schemes, and more reasonable pulse amplitude modulation systems have been produced [4]. So, to solve the fiber-to-the-home problem, large-scale integrated passive optical network technology (PON) continues to develop, and PAM methods for this technology have been developed, such as PAM, Manchester-PAM4 [5]. In addition, owing to the quick growth of cloud services and data center applications, short-range optical link communication systems based on pulse amplitude modulation have received increasing attention,

and four-energy pulse amplitude modulation (PAM4) is widely used in this field, which can offer short-range optical communications with high data speeds at relatively modest prices [6].

It is worth noting that research into the use of PAM pulse amplitude modulated fluorescence measurements has become a hot topic in recent years, with particularly impressive results, building on earlier summaries of systematic phases [7] and refining their application. Some teams have successfully used Pulsed Amplitude Modulated Minimal Fluorescence to determine the biomass of microbenthos [8], and others have used similar methods to measure the photosynthetic intensity of oxygenated and anaerobic photosynthetic organisms in cesspools [9].

In recent years, scientists have come up with a number of effective ways to improve the efficiency and performance of communication systems. Some have focused on improving bandwidth utilisation going for a variety of modulation schemes, including MPMA and some cutting-edge techniques such as a combination of pulse-amplitude modulation and non-orthogonal multiple access techniques, while in this area there is also the cellular large-scale multiple-input multiple-output non-orthogonal multiple access MIMO-NOMA [10], and research into NOMA-related issues. Some scientists have also thought of other measures to improve the efficiency of communication systems, such as innovations in the materials used in devices for LED communication [11], to eliminate LED scattering interference.

This paper examines communication systems using pulse-amplitude modulation, and in Section 3 gives three examples, analyses and compares each of these three distinctive designs, explains the unique innovations of these communication systems, and finally draws a conclusion about the design ideas for pulse-amplitude modulation-based communication systems due to the results of the comparison and analysis.

For the article's main part, the relevant underlying theories are first briefly described in section 2, and in section 3, a comparative approach is used to compare the advantages and disadvantages of different approaches when building the system in terms of the research object, the research scenario, and its possible applications. In the separate analyses, the parts of the system are analyzed in a logical sequence according to the starting point of the system and then to the final summary of the overall system building idea, pointing out its characteristics. That is, the approach of moving from the whole to the parts and back to the whole again introduces a communication system based on pulse amplitude modulation.

This study is applicable to the construction of pulse amplitude modulated optical communication systems, optical fibre communication systems, wireless mobile communication systems and other communication systems associate with PAM, providing some ideas for the initial construction of their simple systems.

2. Basic principles and main theoretical foundations

In this paper, three teams have built pulse-amplitude modulation-based communication systems, involving optical and fibre-optic communication systems. As with the general model of communication systems, the main parts are still the source, a transmitter, the channel part, as well as the receiver, and the host, while the channel provides a path for the signal and also generates various kinds of interference and noise to the signal. In the rest of the presentation, each part will also be analyzed and compared.

As a result of the authors' summary and design, the structure of the pulse amplitude modulation-based communication system in this paper can be summarized by the model shown in the following figure.

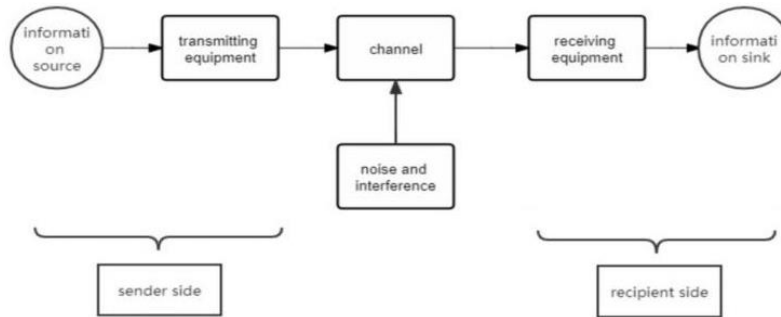


Fig 1. Simple model of a communication system

In section 3.3 of this paper, reference is made to the direct detection (IM-DD) fibre optic communication system, a basic form of implementing fibre optic communication with a similar model to 2.1, where fibre optics are used on the channel.

Since this paper studies a PAM-based communication system, PAM modulation (pulse amplitude modulation), or modified pulse amplitude modulation, is applied in the generation of the signal. With regard to PAM, there are two types of PAMS modulated signal signals that can actually be implemented, one is naturally sampled pulse amplitude modulation, as shown in the diagram, and the other is flat-top sampled pulse modulation. The difference between these two modulation techniques is in how the carrier pulse amplitude varies, in flat-top sampling, the amplitude remains constant throughout the pulse width and the top of each sampling pulse does not change with the signal. In natural sampling, the length of each sampling pulse varies with the signal amplitude, and its amplitude remains constant throughout the pulse width.

Attention should also be paid to whether the sampled signal can satisfy the subsequent experimental conditions when sampling. From Nyquist sampling theorem, it is clear that to retrieve the original signal from the sampled signal and simultaneously avert distortion, the sampling frequency should be 2 times higher than the highest frequency of the signal, and the spectrum of the signal will be aliased when the sampling frequency is less than 2 times the highest frequency of the spectrum, while the signal's spectrum will be free of aliasing when the sampling frequency is more than twice the spectrum's maximum frequency.

In many systems, flat-top sampling is used due to the specific requirements of signal processing, for example, flat-top sampling is applied in the analogue-to-digital conversion part of some systems. In a laboratory environment, natural sampling is used to obtain the original signal in most cases. The signal after natural sampling can be represented by the following equation:

$$\frac{\tau}{T} \sum_{n=-\infty}^{\infty} Sa\left(\frac{nW_s t}{2}\right) M(w - nW_s) \tag{1}$$

As this equation shows, it can be seen that at this point $M_s(w)$ is weighted by the Sa -function and the $M_s(w)$ envelope satisfies the law of variation of the Sa -function and is therefore referred to as the spectrum of the naturally sampled signal. Fig.2 visually depicts the natural sampling process.

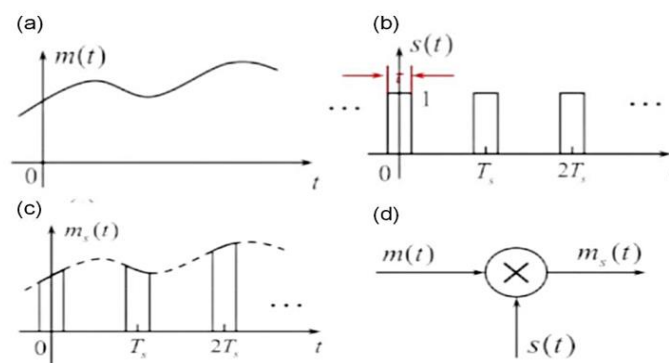


Fig 2. (a) Waveform of baseband analogue signal (b) Pulse carrier signal (c) PAM signal waveform (d) Relationship of the three signals

The PAM-4 and PAM-7 in this article are all PAM-M, the principle of which is briefly explained as follows, the signal of an MPAM can be expressed as

$$\sum_{n=-\infty}^{\infty} A_n g\tau(t - nTs) \tag{2}$$

The interpretation of A_n in Eq. is that let B_n represent a sequence, e.g. the binary sequence $\{0,1,1,0,1, \dots\}$ then A_n is obtained by encoding the B_n sequence, e.g. $A = \{B_{11}, B_2, B_3\}$, $A_2 = \{B_4, B_5, B_6\} \dots$. Also, if the above division is followed, A_n is recognized as a sequence of amplitudes in octal. After passing through the transmit filter, i.e. the forming filter, the signal undergoes changes in the process as shown in Fig.3, after which these electrical signals are sent by the transmitting device to the channel and received by the receiving device. At this point, the design of the communication system is essentially realized.

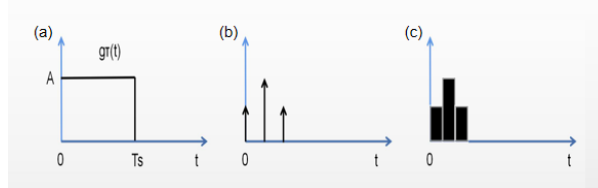


Fig 3. (a) Send filter, (b) Original signal, (c) The signal after passing send filter
 Analysis and comparison of three distinctive communication system

2.1. Two send and one receive Pulse amplitude modulation-based visible light communication system

In the construction of the system, this system was improved based on the traditional single-transmitter-single-receiver communication system model, and after theoretical analysis and calculations, a two-transmitter, one-receiver system was proposed.

In the processing and modulation phase of the information source, the following treatment was adopted, modulating the PAM4 signal on each of the two LEDs and generating the PAM7 signal through the superposition of the optical signals during transmission. At this point it can be observed that the signal has a higher probability of appearing at low level symbols, which will result in a lower average power and a corresponding increase in the peak average power ratio. In addition, in this system, as the power amplifier and other devices at the receive port side also exhibit non-linear properties, the signal that has a large PAPR (Peak to Average Power Ratio) is susceptible to non-linearities and distortion, To solve these problems, the system will be able to use the PAPR as a reference for the signal. To solve these problems, the system designs the PAM7 signal with equal probability, as shown in Figure Fig.4.(a). Seven of the 16 intersection points are then selected as the mapping points for generating the equal-probability PAM7 signal, as shown in Fig.4.(b). In the next step, it is possible to obtain equal probability PAM7 symbols at the receiving end by transmitting symbols at two transmitters with unequal probability and sending only three symbols of different levels at each transmitter. symbols at the receiver. As shown in Fig.4.(b), this coding technique can successfully lessen the signal's inter-code interference, where the two symbols with a smaller interval between adjacent symbols have a less and equal occurrence probability (2/7), additionally, the symbol with the greatest likelihood of occurring has a larger space between neighboring symbols (3/7). Fig.4 is from the original paper [12].

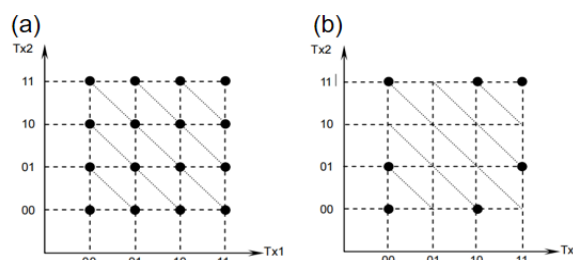


Fig 4. (a) PAM7 signal (b) PAM7 equiprobable signal

In the actual system build, during source processing, the binary bitstream is converted to PAM4 symbols in accordance with the code-mapping rules using MATLAB. The PAM symbols are then PS-Manchester coded for sculpting the spectrum so they can be broadcast instantly in baseband. The encoded PAM symbols are then upsampled by a factor of four and pulse shaped by a Nyquist filter, and the two PAM-4 data streams are fed into two channels of an arbitrary waveform generator (AWG, Tektronix AWG520) to generate electrical signals. To account for the high frequency attenuation of the channel, the two PAM signals from the AWG are routed through a pre-equalization circuit. The equalized signal is then extended by an electric power amplifier (25 dB gain, EA). The RGB-LED lamp's red LED chip whose model is LZ4-00MA00 is connected and loaded through an AC-DC coupler to the amplified electrical signal and the DC bias voltage to drive the LEDs and produce the light signal.

The physical realisation of the light source uses two LEDs at a distance of 1.3 m. After a 1.5 m unrestricted transmission, the PAM-7 signal is created by superimposing the two light signals, converges to the receiver. Two lenses are provided in front of the receiver to focus each light path and to allow the two light paths to converge to the receiver. One photodiode (model: type PINHamamatsu 10784) is employed at the receiver for detecting the signal of received light and convert this received light signal into a signal electrical, which is then extended by an EA and sampled using DSO-Agilent DSO54855A (a kind of digital storage oscilloscope). To enable offline processing of the acquired data, the data is quantified. In the process of offline signal, signal synchronisation, power normalisation, downsampling and differential decoding are executed sequentially to obtain a normalised PAM-7 signal. Then the PAM-7 signal passed through a cascaded multi-modulus method with scalar modifications (S-MCMMMA) based adaptive post-equaliser to eliminate inter-symbol interference. Ultimately, the PAM-7 signal is demodulated according to the code-mapping rules.

2.2. Superimposed pulse amplitude modulated visible light communication transmitter

The system's architecture is also based on conventional communication systems, with innovations to the transmitter section for better use of superimposed pulse amplitude modulation. It suggests a transmitter of visible light using LED that uses PAM-4 modulation and is built with feed-forward equalization (FFE) to make up for the LED device's constrained bandwidth. In addition, a reasonable DC operating environment needs to be established considering the LED device's own constrained linear working area. To be able to take full advantage of the LED's 'multi-colour' nature devices themselves, matching message encoding was also used.

The system is divided into several modules, the LED module, the modulating current control module, the signal input module, the circuit configuration module and the module of output resistance matching. The LED component that emits the light signal, the LED module, is located in the centre of whole working board. The output resistor matching module and the modulating current control unit are connected. Six MAX3668 chips are arranged symmetrically in a module called the modulating current control that receives input signals and produces greater frequency modulating current to regulate the LED's transmission of light. The modulating current control module receives electronic signals from the signal input module efficiently and with the necessary fitting impedance. The circuit configuration modules include movable resistors to allow them to have different operating characteristics, and they are dispersed around the working board's periphery to offer a steady power supply for the entire system.

Based on the physical pictures of the experiments in the text and the discussion of the modules [13], a schematic diagram related to communication system is obtained as shown in Fig.5.

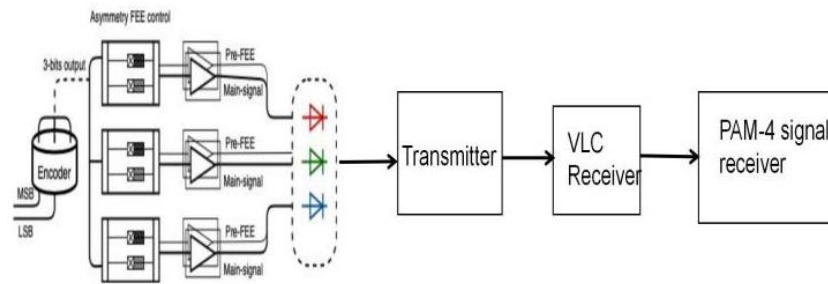


Fig 5. Schematic diagram of a visible optical communication system

The system also has many design innovations. For the layout design and routing of the transmitter components, symmetrical routing and a denser layout are used for noise reduction and signal correction due to performance considerations. To minimize the impacts of noise, the wiring and component locations for the signal pathways are kept as close together as feasible. On the important signal amplitude control pin "modulation set" linked to the chip, a "geometric series resistor" path was built using 5K series, 2.5K series, 1.25K resistors, and sliding resistors. The precision of the output current modification is improved by the control strategy based on an analog circuit.

2.3. PAM modulation-based Reduced-state MLSE for IM/DD systems

Of course, PAM is not only used in visible light communications, but also plays an important role in fibre optic communications, as this example shows. At the same time, this fibre optic communication system improves the MLSE of the receiver part of the common Intensity Modulation-Direct Detection (IM-DD) system, reducing the amount of addition and multiplication operations in the process and lowering its implementation conditions, which is of great practical value.

Firstly, the complexity of the MLSE channel using PAM-M modulation can be defined by the following equation

$$C_{MLSE} = M^L \quad (3)$$

$L+1$ is the length of the delay extension. From this equation it can be seen that even if M is reduced to 1 using a filter, the complexity will still be large. One of the obvious disadvantages of the traditional maximum likelihood estimation equalizer is that due to its complexity the number of lattice states can become huge, particularly large when the channel memory is long and the signal set size is huge.

This Reduced-state MLSE has the following characteristics, Due to the usage of electrical equalization techniques, the main negative impact of bandwidth restriction is waveform distortion brought on by inter-symbol interference (ISI). One way to deal with this distortion is at the receiver, in this case abandoning the traditional method of using a feed-forward equalizer (FFE) to combat ISI and instead using a decision feedback equalizer (DFE).

Fig.6 [14] illustrates the schematic diagrams of the original and upgraded MLSE system. For the conventional method, the general idea is that the impulse response is truncated using a post-filter and linear FFE combo, which will result in a memory length of 2. Since the complexity of the channel is $C_{conventional} = M^{L+1}$, so when L equals 1, the quantity of MLSE-required lattice transitions will be M^2 , Fig.6.(b) shows this, and PAM-4 signaling number is 4^2 , which is 16. A partial response equalizer, which consists of an FFE and a post-filter, is used prior to the MLSE. To truncate the system response, it uses DIR shaping to transform it into a short delayed extended desired impulse response (DIR). Inter-symbol interference (ISI) is addressed by the linear FFE at the expense of noise amplification. The post-filter optimizes the signal-to-noise ratio of the MLSE by shaping the system's impulse response so that it closely resembles the impulse response of the original channel, suppressing the noise amplified by the linear FFE in the process.

For the improved reduced-state MLSE using the PAM-M format for band-limited IM/DD transmission systems, making a rough pre-decision on the signal at the output port of FFE and minimizing the number of states needed in the MLSE are the main goals, this step is based on that

conventional MLSE system described above. The concrete flow diagram is shown in Fig.6.(c), where the pre-decision detector is used as a threshold detector.

As shown in Fig.6.(d), in terms of the final result, the fewer potential symbols under the same conditions successfully lower the updated MLSE complexity, since the complexity of the MLSE is mainly controlled by the number of lattice states, which depends on the number of the most probable symbols.

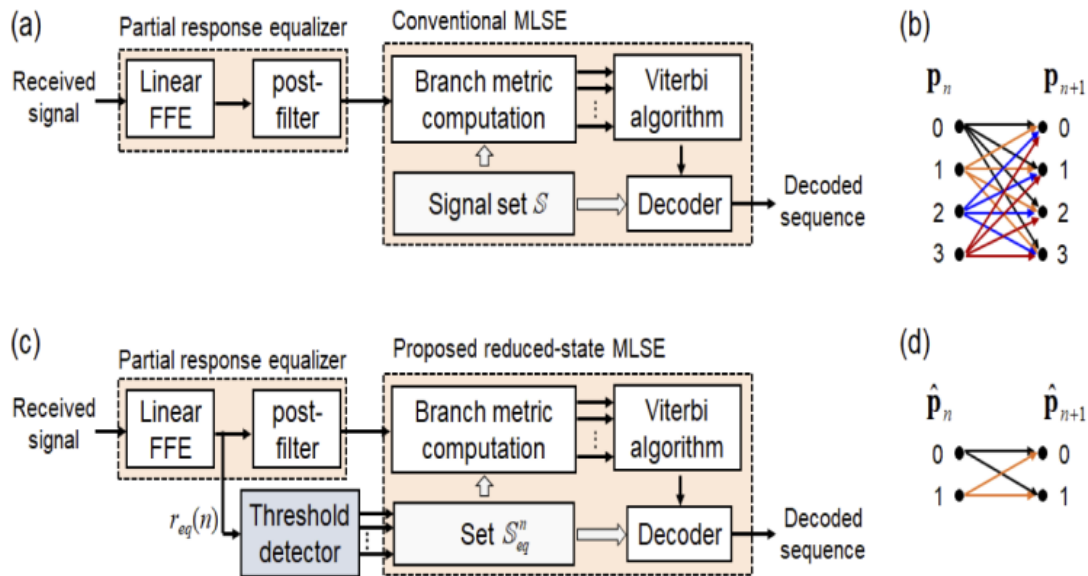


Fig 6. (a) Flow diagram of the transport MLSE (b) Schematic diagram of 4 states and 16 transitions (c) Flow diagram of the proposed simplified state MLSE and (d) Schematic diagram of 2 states and 4 transitions

The team went through and evaluated the performance on 100 to 140-Gb/s PAM-4/6/8 links, a process implemented using 1.31- μm DML. Fig.7 illustrates the overall framework of the system. In this system, the PAM signals are generated offline and then ported to a 6-bit resolution digital-to-analog converter (DAC) with 35GHz bandwidth, which regards PAM-6 generation first maps a 5-bit data to a two-dimensional 32-QAM constellation and projects it on one of the dimensional axes so that it has two PAM-6 symbols. the DAC is set to 1 samples/symbols. The signal is fed directly into the 1313 nm DML, which outputs 12.1-dBm output power when biased at 85 mA. This PAM signal is then broadcast over a regular single-mode fiber and detected using a PIN-TIA detector (band width = 33 GHz) at the detecting end. It is then digitalized in one real-time oscilloscope at eighty Gsamse/s. The waveform that was collected is disposed offline. After detection, the treating processes of digital signal involves resampling, synchronization, electrical equalization, and error counting, which are done under offline conditions and are a key part of the theoretical analysis in this example [14], as well as being an important part of the system's ability to perform pre-decisional functions.

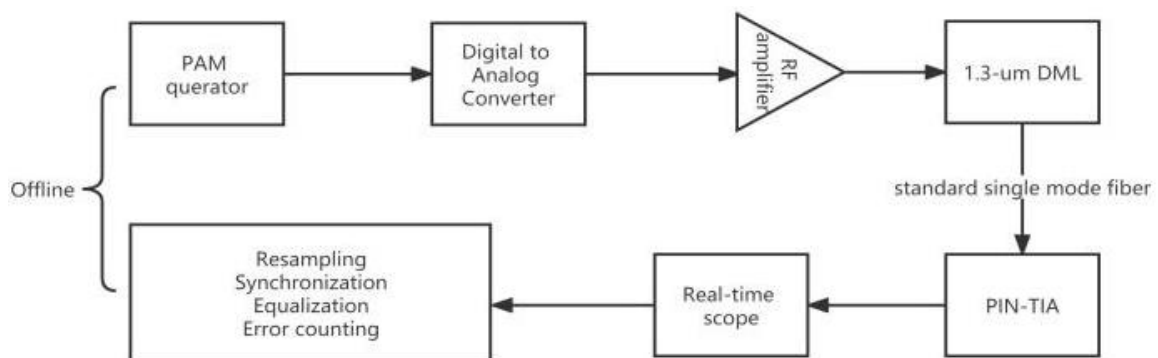


Fig 7. Communication system architecture diagram for simplified state MLSE

2.4. Comparison

Table 1. The Comparison Of The Three Examples

	A	B	C
Study Subjects	Design of a complete optical communication system	Design of a complete communication system	An optimisation of the IM-DD receiver side of a fibre optic communication system
Research scenarios	Visible light communication, short range communication	Visible light communication, indoor communication	Fiber Optic Communication
Innovative approaches	Focusing on the PAM signal generation stage, a new coding and mapping scheme is designed for the superposition of two low-order PAM4 signals in the optical domain to produce a high-order equal-probability PAM7 signal.	In this scheme, a dense signal path layout is used for signal compensation and noise reduction.	Extensive mathematical and theoretical analyses were carried out to design the pre-decisional functional part, resulting in the implementation of the simplified state MLSE.
Optimization directions	is a further optimization of the performance of the base system, with a focus on the transmitter side	is a further optimization of the performance of the base system	It is an optimization of the functionality of the receiver side of the base system that reduces the complexity of the circuit implementation while ensuring that the system functionality is achieved.
Possible application aspects	The two-receiver, one-transmitter communication system is an improvement on conventional optical communication systems and can be adapted to all designs of applications to short-range optical communication systems.	Design of communication systems for indoor scenarios, for systems that need to emit white light while fulfilling the function of visible light communication, as screen backlighting for display systems, for example in commercial displays.	Applications are on the receiving end of bandwidth-intensive applications such as media services, cloud storage and data centres, and can also be used as a replacement for the receiving end of MLSE's IM-DD system, making the original system more economical and commercially viable.
Type of pulse amplitude modulation used	PAM7 modulation deduced from PAM4	PAM-4	Multi-state pulse amplitude modulation

In terms of commonalities, all three improve on traditional communication systems by making significant improvements in one area of functionality.

In both examples, section A and B, the transmitter system has been optimized. Both have the same design philosophy of complicating the transmitter side so that more functions can be implemented at the transmitter side, allowing for a more desirable signal in the subsequent modulation process, or some complex functions to be implemented at the transmitter side.

In contrast, the optimization in section three, C, focuses on simplifying the conditions for the realization of the system, through complex theoretical derivations, to obtain a simplified system with essentially the same functionality as the original system.

By comparing the three systems, we can appreciate that when designing a communication system, we should first define the direction of the design, whether to improve functionality or to try to meet low complexity while achieving basic functionality. The ideal state of a communication system is one that is both functional and simple, but in practice it may not be possible to achieve both for a variety of reasons, so there is a trade-off to be made. In the three examples analyzed in this paper, it can be seen that all three have their own design priorities, like C in section 3, where more devices have been added to the structure in order to achieve functional simplicity and efficiency, resulting in a higher level of complexity than the original system. In practice, of course, we can then aggregate the advantages of each of these systems to build a more scientific and efficient communication system.

3. Conclusion

In this context, I propose the basic idea of a pulse amplitude modulation based communication system. Firstly, based on the functions to be implemented in the system, choose the appropriate type of PAM, refer to the conventional communication system model (Fig.1) and decide in advance which parts need to be enhanced and which parts need to be simplified in terms of the actual circuit implementation, while striking a good balance between functionality and complexity. If there is a requirement for the type of signal at the transmitter, e.g. a PAM4 signal is required, then the transmitter is improved (e.g. A in section 3), and if there is a requirement for the signal at the receiver, then the receiver is refined or the system is restructured, e.g. by adding feedback branches to the whole system (e.g. C in section 3). Theoretical derivations are then made to derive the theoretical basis for the functions that need to be achieved in each part. Finally, the original system is optimized in conjunction with the resulting physical system, and the process is repeated until a satisfactory system is obtained. In short, it is a process of moving from the whole to the local, from theory to practice, and then iteratively to renewal.

After comparison and analysis, it is clear that no matter how complex a communication system is, the process of building it is based on the traditional framework of communication systems, as well as the process of building a new communication system is in fact a process of optimizing it and matching it to the functions that need to be achieved. In the case of this paper's design of a pulse amplitude modulation based communication system, the focus is on how to achieve this and which method to use to achieve PAM modulation and demodulation of the signal at both the transmitter and receiver ends.

As mentioned above, PAM has been developed for quite some time, the traditional pulse amplitude modulation theory has been perfected, new pulse amplitude modulation has been updated, and PAM-based communication systems are becoming more and more powerful. Nowadays, pulse amplitude modulation is widely used in fibre optic communication, optical communication, wireless mobile communication, RF related fields and even in other disciplines, and the design of pulse amplitude modulation-based communication systems will remain a hot topic for a long time to come.

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