Research on ASK modulation and demodulation algorithm and performance optimization in high frequency millimeter wave scenario

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Abstract. Amplitude Shift Keying (ASK) is a modulation technology with a very simple principle and extremely low cost. It is widely used in many fields today. For example, it is used in scenarios that we often encounter in our daily lives, such as Radio Frequency Identification (RFID), access control systems, and bus cards. Moreover, it is also widely applied in control systems, such as health monitoring of biological implants and tire pressure monitoring systems. It can be seen that ASK occupies a very important position. However, with the rapid development of 5G-Advanced and 6G short-range communication, the application in high-frequency and ultra-high-frequency has increasingly become a key technology of the era. In these scenarios, our traditional low-frequency ASK technology is affected by many factors, resulting in poor performance, failure and other outcomes. This paper identifies the root causes of performance degradation in high-frequency implementations and proposes optimization solutions like memristor modulators. Furthermore, the study outlines future research directions for these improvements, establishing a theoretical foundation for enhancing ASK technology's applicability in high-frequency environments.

Keywords: ASK Modulation and Demodulation, Low-Frequency Scenarios, High - Frequency, Scenarios, Optimization Solutions.

1. Introduction

Digital modulation technology has become increasingly prevalent in modern society, enabling the transmission of digital information through various techniques into analog channels. Among modulation methods, ASK has emerged as the most widely adopted due to its simple principles and lower hardware costs [1]. This straightforward and cost-effective modulation technique is extensively utilized in daily applications such as RFID, access control systems, and public transportation cards. Its core mechanism involves modulating carrier signal amplitude to represent binary digits (1 and 0, where 0 indicates no carrier presence while 1 signifies active transmission). Additionally, ASK finds applications in control systems including biomedical implant health monitoring and tire pressure detection systems, while also playing a vital role in IoT and biomedical electronics [2]. Although the anti-noise ability of ASK may not be comparable to that of technologies such as Phase Shift Keying (PSK) or Frequency Shift Keying (FSK), It holds irreplaceable advantages in terms of technical complexity, signal loss, and cost-effectiveness. This explains its significant position in technological development. With the rapid advancement of 5G-Advanced and 6G short-range communications, high-frequency and ultra-high-frequency applications are becoming pivotal to contemporary technologies. However, with the increasing prevalence of high-frequency and ultra-high-frequency applications, challenges such as excessive transmission loss, severe Doppler frequency shifts, and inadequate high-frequency multipath modeling have resulted in alarmingly high bit error rates. These factors hinder the full utilization of ASK technology's capabilities in high-frequency scenarios, leading to unsatisfactory practical performance.

This research report provides a comprehensive analysis of the core principles governing the entire ASK "modulation-channel transmission-demodulation" chain. It identifies the root causes of performance degradation in high-frequency implementations and proposes optimization solutions like memristor modulators. Furthermore, the study outlines future research directions for these improvements, establishing a theoretical foundation for enhancing ASK technology's applicability in high-frequency environments.

2. The Modulation and Demodulation Process of ASK

The model of ASK modulation and demodulation technology can be divided into three parts. The complete path includes three steps: ASK modulation, channel transmission and demodulation recovery. ASK Modulation and Demodulation is shown on Fig.1.

Fig. 1 ASK Modulation and Demodulation (Picture credit: Original)

2.1. The transmitter model

In this process, the binary data information will be converted into analog signals and can pass through the channel. In this conversion process, the ASK modulation technology is used. At this step, the ASK modulation process is performed. Modulation is the process of converting baseband binary data ("0" and "1") into high-frequency carrier signals. The essence of modulation lies in creating a connection between the data and the amplitude of the carrier signal. The principle of ASK modulation is as follows: Upon sending "1," the transmitter will produce a continuous signal wave characterized by a consistent amplitude and frequency; when sending "0", the transmitter will not send any signal. This demonstrates that the ASK modulation process enables "baseband signal control of RF switches". If the baseband signal is 1, the switch closes, making the carrier signal pass through successfully. Conversely, when the baseband signal is 0, the switch opens, blocking any signal transmission.

$$s(t)=\begin{cases} A\cos(2\pi f_c t+\varphi_0), & \textit{when transmitting } \text{"1"} \\ 0, & \textit{when transmitting } \text{"0"} \end{cases} \tag{1}$$

2.2. The channel model

The channel is the inevitable path connecting the two steps of ASK modulation and ASK demodulation. In the channel, there will be additive white Gaussian noise. In the high frequency or ultra-high frequency environment, the signal transmission in the channel will produce attenuation, such noise can severely degrade the quality of the final signal received by the receiver (directly reducing the signal-to-noise ratio, which in turn increases the bit error rate). The bit error rate (BER) – defined as the percentage of bits that are incorrectly received – serves as one of the most critical performance indicators. Meanwhile, the signal-to-noise ratio (SNR) measures the power of the useful signal relative to the total noise power in the received signal.

$$\text{SNR(dB)}=10\log_{10}\left(\frac{P_s}{P_n}\right) \tag{2}$$

Then the signal power formula and the noise power formula $P_s=\frac{A_r^2}{2}$, $\boldsymbol{P}_n=\frac{N_0 B}{2}$. Go further, SNR (dB)$=10\log_{10}\left(\frac{A_r^2}{N_0 B}\right)$.

Therefore, it can be known that the signal-to-noise ratio is proportional to the square of the received amplitude, the channel bandwidth, etc. Besides, the larger the carrier amplitude A, the higher Eb and SNR, the smaller the noise interference, and the lower the BER. If noise is superimposed on the transmitted signal, it may cause distortion of the received signal. In this case:

$$r(t)=\begin{cases} A\cdot\cos(2\pi f_c t)+n(t) & \text{when transmitting "1"} \\ n(t) & \text{when transmitting "0"} \end{cases} \tag{3}$$

The formula for free-space transmission loss is:

$$L(\mathrm{dB})=20\log_{10}\left(\frac{4\pi d f_c}{c}\right) \tag{4}$$

From the formula, transmission loss is proportional to the square of the carrier frequency. In addition, in high frequency environment, the amplitude of the received signal will be weakened very much, so it is necessary to increase the power to achieve continuous demodulation.

2.3. The receive model

Finally, when in the receive model, ASK demodulation and ASK modulation are two opposite processes. It restores the signal obtained in the ASK modulation process into the original binary digital data. This enables the demodulation of ASK, which can be divided into two demodulation process methods in total: coherent demodulation and non-coherent demodulation. Following diagram shows the specific processes of these two methods. The processes of coherent and non-coherent demodulation are shown on Fig.2.

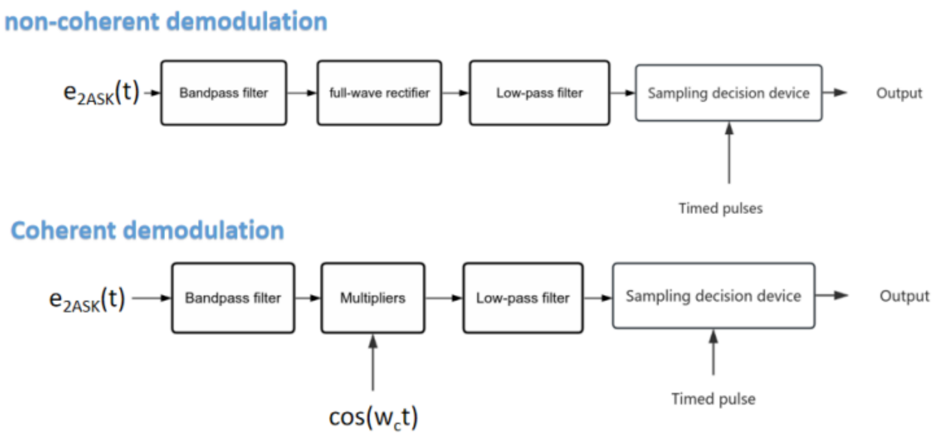

Fig. 2 Coherent and Non-coherent Demodulation (Picture credit: Original)

When it comes to the calculation of the bit error rate of the demodulation method, conduct an analysis by category. In coherent demodulation, when the decision threshold reaches the optimum, $P_e=Q\left(\sqrt{\frac{SNR}{2}}\right)$, and therein lies the problem, $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{+\infty} e^{-\frac{u^2}{2}}$.

In non-coherent demodulation, $P_e=\frac{1}{2}e^{-\frac{SNR}{4}}$, From this, the bit error rate (BER) of non-coherent demodulation is only related to SNR and has nothing to do with carrier phase.

3. The bottlenecks faced by ASK in high-frequency scenarios

3.1. Application Status in Low - Frequency Scenarios

ASK itself is inherently simple, which makes it cost-effective and energy efficient, so ASK has become the first choice for many applications and research in low-frequency environments.

3.1.1. Low frequency card system.

Its application is everywhere in daily life today, and it refers to access control cards, keypads, car keys and other applications. In this application scenario, ASK has been developed over decades with highly mature technology. The principle involves storing identity information as binary data within the card. During ASK modulation, the binary data is converted into radio frequency signals with specific amplitude variations. When the receiver performs ASK demodulation, it uses a non - coherent demodulation method. Through bandpass filtering to eliminate environmental noise, followed by full-wave rectification and low-pass filtering processes, the RF signals are ultimately restored to their original binary format. In this way, it can help readers successfully identify and respond to signals. In such environments, it achieves exceptionally low error rates, stable performance, and minimal operational errors. Compared to other modulation technologies, ASK offers remarkable cost-effectiveness while providing significant societal value. And card applications also occupy a very important position in the low frequency RFID market. In 2019, it eventually occupied about 87% of the low frequency RFID market, which shows its social importance.

3.1.2. Memristor-based ASK Modulator

The traditional construction of ASK is often related to analog multipliers and switching circuits. A memristor is a nonlinear, two-terminal resistor with memory. It changes its own resistance when the amount of charge or magnetic flux flows through it changes. Therefore, if voltages of different polarities are applied to it, the resistance will also change accordingly, and because it's affected by the amount of charge or flux that's been flowing through it before, When the power is cut off, its state will not change due to the open - circuit state. In this application, the varying resistance of the memristor itself can represent different amplitudes of the ASK signal [3].

The working principle is as follows: First, an input signal is fed into the memristor modulation circuit with a low-frequency carrier signal. Next, ASK modulation converts the binary data representing information into control voltage pulses. When the digital value is 1, the memristor reaches a certain charge level and becomes low-resistance. When the value is 0, no charge flows through the memristor, resulting in high resistance. Finally, the output signal is obtained and the ASK signal is obtained. In addition to retaining the advantages of traditional ASK modulation technology, this application also has significant advantages. The memristor can maintain the previous resistance state after power failure, and has memory, which plays a role in storage applications.

Current applications: Due to memristors' unique nonlinear electrical properties and memory capabilities that enable encrypted ASK signals, they serve as a security safeguard. In some implantable devices, these components play an indispensable role. For instance, in brain-computer interfaces and cardiac pacemakers, they facilitate the transmission of patient data to external receivers, thereby enhancing operational efficiency. The ASK modulator based on memristor is currently in the research stage of low frequency and low speed environment, which lays a foundation for future high frequency or ultra-high frequency applications.

3.1.3. Modulation format conversion in optical communication

The controllability and convertibility of ASK signal to provide a direction for the application in low frequency environment. This is a current conversion method implemented in a semiconductor optical amplifier (SOA), based on cross polarization modulation (CPM), to achieve the full optical modulation format conversion from ASK to PSK. This study proposes an innovative approach to demonstrate the adaptability of ASK baseband technology. It demonstrates that ASK can be used as a fundamental modulation method even in low-frequency environments, rather than relying solely on ASK itself. By integrating ASK technology with other channel-forming formats suitable for low-frequency channels or combining it with other modulation techniques (such as PSK), the paper enhances its inherent advantages while achieving improved anti-interference capabilities.

Research demonstrates that ASK signals can be efficiently converted into FSK signals. Moreover, the resulting FSK signals feature adjustable tone intervals that can be modified by adjusting the frequency of the input detection light. This indicates that ASK signals are capable of being manually controlled. In addition, the ASK signal can also be used as an "information carrier". In the low-frequency environment, it can achieve information encoding source with only low power consumption and convert the signal to the frequency band most suitable for the low-frequency environment, so as to achieve anti-interference and other capabilities.

3.2. Performance Bottlenecks in High - Frequency Scenarios

Although the advantages of ASK technology, such as simple principle and low cost, are indeed very advantageous in many daily fields, its disadvantages are also obvious in high-frequency scenarios. There are three kinds of bottlenecks: channel and propagation bottleneck, device and hardware bottleneck, and signal processing and system bottleneck.

3.2.1. Channel and propagation bottleneck

Similar to laser-to-microwave transmission and free-space optical communication, signal power experiences a sharp decline as transmission distance increases [4]. In higher frequency environments, this attenuation becomes even more pronounced. When transmitting over extended distances, this results in significant path loss, which fundamentally limits the communication range of ASK technology. Moreover, the weather environment will also affect the transmission quality of ASK in the channel. In bad weather (such as fog, rain, snow, etc.), high frequency signals are easily absorbed, resulting in a sharp attenuation of signal strength, which is also an urgent problem to be solved in high frequency environment [5].

3.2.2. Device and hardware bottleneck

The foremost challenge in such scenarios lies in power consumption. When operating at high frequencies (including microwave, millimeter-wave, and even optical frequency bands), achieving high-speed signal processing and switching inevitably requires substantial energy expenditure. Consequently, applications requiring power efficiency as the primary constraint – particularly mobile devices and implantable electronics – often fail to benefit from ASK-based solutions.

Recent advancements in photonics have enabled the generation of high-frequency microwave signals. However, this process requires components with exceptional precision, such as lasers. While these technologies can enhance the performance of ASK systems in high-frequency environments, their substantial costs make widespread adoption in daily life impractical [6].

3.2.3. Signal processing and system bottleneck

In high-frequency environments, carrier frequencies are extremely high, resulting in short cycles. Consequently, even minor timing errors can significantly increase bit error rates, leading to reduced signal accuracy and poor reception quality. This demonstrates that ensuring signal precision requires highly accurate synchronization methods, which substantially increases the complexity of the system.

Furthermore, security concerns and signal interference remain critical factors affecting the effectiveness of ASK-based systems in high-frequency environments. Unlike low-frequency applications with shorter transmission distances, high-frequency systems face greater risks of eavesdropping and signal disruption due to longer communication channels. To mitigate these vulnerabilities, enhancing encryption capabilities and anti-interference measures becomes essential. However, this approach inevitably increases operational complexity and costs.

Based on the above main bottleneck factors in high frequency environment, performance improvement in high frequency environment is often accompanied by power consumption, complexity and cost increase. Therefore, the paper needs to find a good balance to achieve the most cost-effective method.

4. Optimization Solutions for ASK in High - Frequency Scenarios

4.1. Channel and propagation

It is known from the research that SWIPT collaborative design is a good optimization scheme. Its principle is as follows: for the overall system which carries out wireless information and data transmission at the same time, the design parameters of the integrated receiver are optimized to find a balance that can best balance energy efficiency and bit error rate.

In the face of bad weather, multi-dimensional optimization of free-space optical communication is a good way to optimize. It mainly reserves enough power margin in advance, uses multiple transmitters or receivers, and ensures data reliability by automatically retransmitting when the link is interrupted.

4.2. Device and hardware

Integration and monolithic design we can consider achieving the effect of optimization. First, understanding the concept of integrated design is the key, which is the integration of multiple functional circuits into a single chip, thereby reducing external wiring [7].

He optimized the technical performance of ASK in high frequency environment in Dalian from the following aspects. First, it can significantly reduce power consumption. We know that using a large capacitive load will definitely consume a huge amount of power, and in this process, the interface circuits between discrete chips will also consume power. However, the capacitive load inside a monolithic chip is extremely small, and the internal modules of the chip can communicate directly through low-swing signals, thereby significantly reducing power consumption.

What’s more, it can reduce volume and cost. This process requires a large number of chips and PCB area, resulting in a very large volume, and the packaging, testing, and assembly of each component all increase costs. However, monolithic integration brings them all together, achieving miniaturization and greatly reducing the occupied volume. Thus, integrating things like high-frequency ASK transceivers into very small devices is useful, thereby reducing volume and cost.

Finally, it can improve performance consistency and reliability. There are certain errors in the parameters of different discrete components, and these errors are not fixed. They will drift with changes in the surrounding environment such as temperature and humidity, which will lead to defects such as unstable system performance and low reliability during mass production. Therefore, in order to avoid such defects, the paper adopts the method of manufacturing different components on the same silicon wafer. Components manufactured in this way have better parameter consistency and high temperature characteristic matching, thereby significantly improving the consistency of key parameters, having strong anti-interference ability, and the optimization effect is very obvious.

Therefore, the reduction in power consumption, shrinkage in size, and improvement in reliability brought about by integrated and monolithic designs cannot be achieved by any other optimization technology alone.

5. Future Prospects

The future may see more communication systems constructed using non-traditional CMOS components such as memristors, phase-change materials, and topological insulators. These systems can achieve efficient modulation and transmission while storing or sensing data, significantly reducing power consumption and latency in IoT nodes [3].

Two-dimensional materials such as graphene and transition metal sulfides (TMDs) may also be used more widely in the construction of ultra-high-speed and tunable optical modulators and detectors due to their excellent photoelectric properties, which can promote the development of integrated photonics [8].

Photonics-assisted technology will become the core innovation for 6G and future wireless communication front-ends. By generating and distributing pure millimeter-wave and terahertz signals through photonics, it addresses bandwidth limitations, noise interference, and synchronization challenges inherent in purely electronic approaches. Furthermore, "laser-microwave" transmission and Free Space Optics (FSO) technologies may pave the way for constructing high-speed, high-capacity space backbone networks, enabling secure communications between satellites, between satellites and Earth, underwater systems, and even across drone swarms [9].

In the most widely used ASK technology, security remains the paramount enhancement direction. Confidentiality can be enhanced based on channel characteristics, memristor characteristics, quantum noise, etc. In the future, if technologies such as ASK or PSK are used for data transmission, and quantum signals (such as quantum key distribution, QKD) are simultaneously used to distribute encryption keys, it will enable high efficiency while ensuring absolute security [10].

6. Conclusion

This study provides a comprehensive analysis of Asymmetric Shift Keying (ASK) modulation technology. As a classic and simplest modulation method, ASK demonstrates distinct advantages across different frequency environments. In low-frequency applications, ASK technology stands out as the most widely adopted modulation approach due to its simple principles, cost-effectiveness, and energy efficiency. However, when ASK technology enters the high-frequency environment, it faces a very significant challenge. The defects such as huge path loss, atmospheric attenuation and high-power consumption make its performance improvement encounter a bottleneck. In order to overcome these bottlenecks, optimization schemes such as photon-assisted signal generation, integration and monolithic design are proposed. These schemes can effectively improve the performance of ASK technology in high-frequency environment. In the future, the development of ASK technology may be combined with new materials and architectures to continue to play a role in other areas such as 6G, Internet of Things and ultra-low power communications.

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