A Review of Communication Technologies in Mud Pulse Telemetry Systems

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Abstract: Mastering real-time and accurate downhole information is crucial for ensuring drilling safety, improving drilling efficiency, and maximizing economic benefits. In recent years, logging while drilling (LWD) technologies, represented by mud pulse telemetry (MPT), achieved significant success. However, they still face challenges such as a large amount of downhole information conflicting with low information transmission rates, severe channel distortion, strong noise interference, and weak surface receiving signals. Therefore, this review collects and updates the papers, patents, and conference articles in the relevant field over the past ten years. Starting from the basic structure of communication systems, the downhole signal coding and modulation technologies of the MPT system are discussed. The attenuation reflection brought by the mud channel and various noise interferences in the system are described. The surface noise cancellation, channel equalization, synchronization, and decoding are studied in detail. By analyzing the theoretical principles, development breakthroughs, and relevant challenges that can improve the development of LWD technologies, this review aims to assist researchers in the field in obtaining the latest references and strategies.

Keywords: logging while drilling (LWD); mud pulse telemetry (MPT); communication system; noise cancellation techniques

1. Introduction

Petroleum, as a fundamental energy source, is widely used in industrial production and transportation. It is an indispensable strategic resource for production, livelihood, economic development, and even national security. For a long time, the exploitation conditions in oil wells have become increasingly harsh, and the amount of downhole information has continued to increase, so it is necessary to adopt more advanced logging technology. Compared with traditional logging technology, LWD is able to obtain real-time and accurate dynamic parameter information (such as temperature, inclination angle, geological resistivity, natural gamma, etc.) while drilling in deep reservoirs and unconventional reservoirs. The acquired drilling and formation information help surface engineers make better drilling decisions, control drilling status, improve drilling efficiency, and reduce production risks and costs [1]. As shown in Figure 1, the LWD technology plays a vital role in the design and application of directional wells, especially horizontal wells, multi-branch wells, and extended-reach wells. For previous no-go reservoirs with very challenging drilling environments, such as high-pressure and high-temperature environments or extremely complex geological environments, the utilization of LWD has made exploitation possible [2,3]. Therefore, in recent years, the increasing demand for LWD has led to its rapid development, but it still faces challenges such as slow transmission rates, unstable signal quality, and an emerging plethora of theoretical methods without a perfect one.
As shown in Figure 2, the LWD telemetry system is a typical communication system, which includes the downhole sensor unit, downhole data telemetry unit, and surface signal processing unit [4]. The downhole sensor unit includes various downhole sensors, which are responsible for obtaining data such as the current drilling status and geological characteristics in real time. The downhole data telemetry unit includes a signal generator and transmission channel. Its main function is to convert the acquired data into signals suitable for channel transmission using reliable coding and modulation techniques and transmit the data to the surface via wired or wireless channels. The surface signal processing unit includes signal receivers (such as acquisition cards) and signal processing equipment (such as computers), which are responsible for optimizing and identifying the received signals and recovering downhole information.

Figure 1. Schematic diagram of five typical kinds of wells.

Figure 2. Schematic diagram of the LWD telemetry system.
This paper focuses on the latest communication techniques such as coding and modulation, channel modeling, and signal processing in MPTS systems. The most important step in surface signal processing is noise suppression. Therefore, in addition to the conventional classical noise suppression scheme, this paper incorporates the application progress of Deep Learning in surface signal processing. As shown in Figure 3, this paper divides the processing flow of original telemetry data into three parts: coding and modulation of downhole data, channel characteristic research, and surface signal processing. The specific structure is as follows: Section 2 introduces the types, characteristics, technical principles, and existing challenges of LWD telemetry systems. Section 3 focuses on the coding and modulation techniques for downhole data in mud pulse telemetry systems. Section 4 analyzes the mud channel model and various interferences existing in the channel. Section 5 introduces surface signal processing techniques, discussing key measures such as noise reduction, channel equalization, synchronization, and decoding of surface signals. Section 6 provides a summary of the entire paper and a future discussion of MPT development.

![Flow chart of original telemetry data processing.](image)

**Figure 3.** Flow chart of original telemetry data processing.

## 2. Overview of LWD Telemetry System

The LWD system can be categorized into wired and wireless transmission modes. Common wired transmission methods include wired cables, specialized drill pipelines, and optical fibers [5]. The wired transmission offers advantages such as high speed and simplicity in principle. However, in deep well applications, the installation of wired connections from the downhole to the surface results in expensive initial costs, complex operations, and difficulties in later maintenance. On the other hand, wireless communication avoids the difficulty and high costs associated with constructing wired communication infrastructure in complex downhole environments [6]. Wireless systems can be flexibly modified and possess high portability, allowing for adaptation to different application environments. Common wireless transmission methods include electromagnetic (EM) waves, acoustic waves, and drilling fluid pressure waves represented by mud. Other wireless downhole telemetry technologies that could be explored in the future include chemical telemetry, thermal telemetry, and nuclear telemetry [7].

The EM-LWD system utilizes the formation and drill string as the transmission channel and employs low-frequency electromagnetic signals as the transmission carrier. The advantages of the EM-LWD system lie in its simple structure without moving parts and a high transmission rate [8]. Additionally, it is particularly suitable for underbalanced drilling or air drilling operations [9] and it can transmit annular pressure data when the pump is shut down, which provides valuable information for studying the hydraulic behavior of the wellbore during pump shutdown [10]. However, this transmission method also has some drawbacks. The signal attenuation degree of the EM signal becomes serious with the increase in the depth of the stratum, and the quality of signals is closely related to the formation resistivity [11]. It is necessary to analyze electromagnetic field models according to the characteristics of different formations and evaluate the impact of formation and noise on the attenuation of EM signals.

There are various methods to improve the application depth of EM-LWD technology. Lu et al. [12] studied an EM-LWD system that receives signals from adjacent wells, which significantly increases the voltage value of the received signals on the surface.
The voltage increases as the neighboring well becomes deeper, thereby enhancing the receiving signal intensity of the EM-LWD system. In addition to software improvements, hardware solutions can also be considered, such as using multiple electromagnetic relay devices to receive and retransmit signals, but this increases cost and complexity. In summary, EM-LWD systems have certain technical advantages in specific environments. However, they also suffer from severe signal attenuation, shallow drilling depth, and limitations in deep-water operations [13]. It is also these deficiencies that cause the EM-LWD system not to be widely used.

The acoustic wave LWD system commonly utilizes the drill string as the transmission channel and employs acoustic waves as the transmission carrier. In recent years, studies have also pointed out that there is significant potential for using drilling mud inside the drill string as the transmission channel [14], but the propagation of acoustic waves in high-velocity drilling fluid poses greater challenges. The biggest advantage of the acoustic LWD system lies in faster data transmission rates, which can reach hundreds of bits per second. However, the system has limitations such as multipath propagation, signal attenuation, and reflections that result in a low signal-to-noise ratio (SNR) at the surface receiver. Therefore, repeaters are often required to amplify the signal, making system construction and maintenance complex and expensive [15].

Shin [16] studied a transient numerical model that can effectively reflect the attenuation of acoustic signals. This model considers energy dissipation factors caused by viscous friction and can serve as a virtual testbed for developing various acoustic telemetry communication algorithms to overcome signal attenuation and improve communication performance. Pelekanakis et al. [17] proposed an acoustic telemetry system combined with multicarrier modulation. Simulation results showed that the proposed system achieved a transmission rate of 400 bps in a 1 km realistic drill string channel model. One challenge in the practical implementation of acoustic telemetry systems is selecting the appropriate carrier frequency. Since acoustic wave transmission relies on the drill string, the impedance mismatch caused by the non-uniformity at the drill string connections results in frequency passbands and stopbands, making it crucial to ensure the signal frequency falls within the passband. Mostaghimi et al. [15] proposed a dynamic drill string model that can accurately detect drilling conditions in real time. This model, built upon the analysis of existing drill string models, provides a good estimation of the passband frequency range required for acoustic signal transmission.

Currently, as the most widely used LWD technology, MPT utilizes the flowing mud inside the drill string as the transmission channel. It offers advantages such as robustness, long transmission distances, and wide applicability, making it extensively used and recognized in downhole data transmission [18]. However, a main disadvantage of MPT is its slow transmission rate. In the face of the increasing demand for real-time data rates, researchers have developed high-speed mud pulse telemetry (HSMPT) systems that can achieve transmission rates of up to 10 bits/s or even higher [19], although it is still not sufficient. MPT poses significant challenges in certain drilling scenarios that involve air or gas-containing mud [20]. Additionally, MPT systems can be affected by mud erosion, channel multipath effects, mud pump noise, and the instability of high-viscosity fluid states. Therefore, realizing high rates, good reliability, and economic feasibility of MPT systems remains a major research focus.

The MPT systems can be categorized into positive pulse, negative pulse, and continuous-wave (CW) MPT according to different signal forms, as shown in Figure 4 [1]. Positive pulse technology is relatively mature, with stable communication performance, and is the earliest to be applied in the market. However, it has a slow data transmission rate, mostly ranging from 0.5 to 1.5 bits/s [21]. Negative pulse technology has lower transmission rates and higher energy consumption. Additionally, the wellbore is prone to corrosion by the drilling mud, limiting its application. Compared with positive and negative pulse technologies, CW-MPT technology appeared later and is more advanced in terms of principles and techniques. Its advantages, such as high transmission rates, good reliability, and cost-effectiveness, have
made it a major research direction in LWD telemetry [22]. The characteristics of different LWD telemetry systems are summarized in Table 1.

Figure 4. Mud pulses: (a) positive-pulse, (b) negative-pulse, and (c) continuous wave.

Table 1. Comparison of characteristics of different LWD telemetry systems.

<table>
<thead>
<tr>
<th>Features</th>
<th>MPT</th>
<th>EM</th>
<th>Acoustics</th>
<th>Wired Drill Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>Lifetime at 100 °C (yr)</td>
<td>5+</td>
<td>N/A</td>
<td>5+</td>
<td>1–2</td>
</tr>
<tr>
<td>Signal attenuation</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Requires repeaters</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum rate (bps)</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>&lt;10</td>
<td>&lt;400</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>&gt;6000</td>
<td>&gt;6000</td>
<td>&lt;6000</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Major advantage</td>
<td>stability</td>
<td>stability</td>
<td>data rate</td>
<td>data rate</td>
</tr>
<tr>
<td>Major disadvantage</td>
<td>data rate</td>
<td>erosion</td>
<td>attenuation</td>
<td>cost</td>
</tr>
</tbody>
</table>

The three different pulse signal generation methods correspond to different pressure wave generators. For example, the rotor is a core component of the CW signal generator in drilling mud [23]. The design of the valve hole structure and synchronized motor drive in the signal generator are of significant importance for generating high-quality pulse signals, improving the performance of the MPT system and achieving high-speed transmission of downhole information [24]. Additionally, erosion of the mud and friction between components can bring losses to system components. Therefore, selecting appropriate metal materials for manufacturing components of the MPT system can greatly improve their mechanical performance and service life, reducing maintenance costs and enhancing drilling efficiency [25]. The mechanical design and automatic control of the signal generator are critical technologies that significantly impact the quality of mud pulse signals, but further details will not be discussed here. Next, this paper will focus on analyzing the coding and modulation, channel modeling, signal denoising, equalization, and synchronization techniques associated with MPT systems, which are crucial for improving the communication performance of the system.

3. Coding and Modulation of the Mud Pulse Signal

The real-time data collected by the downhole sensor unit needs to be transmitted from the bottom of the well, which can be hundreds or even thousands of meters deep, to the surface. The harsh transmission environment of the mud channel makes the received signal prone to attenuation and distortion. Therefore, by encoding and modulating the original data, not only the data transmission efficiency is improved but the anti-noise performance of the system is also greatly enhanced. When selecting specific coding and modulation formats, it is important to consider the characteristics of the processed signal with less DC component, more stability and reliability, and ease of detection and recognition at the surface [26].
For positive MPT systems, the data is coded and transmitted to the surface in the form of discrete pressure pulses via the baseband. There are various coding formats suitable for mud pulse signals, and different methods have different technical characteristics. Tu et al. [27] analyzed the transmission format and characteristics of the pressure pulses based on Manchester codes. Manchester codes have no DC component and strong anti-interference capability, but they suffer from low coding efficiency. Liang et al. [26] proposed a high-rate signal transmission coding format based on Miller codes. Miller codes have no DC component and are easy to detect, but the transition points in the middle can be influenced by complex noise in the wellsite. Zhang et al. [28] used pulse location modulation (PLM) techniques to encode mud pulse signals by combining M pulses with N slots. This approach achieved a high transmission rate, but the complexity of the coding scheme made detection challenging. Hua et al. [29] used combination codes to encode data based on the characteristics of pressure pulse transmission, which can obtain shorter transmission times and higher fault tolerance. However, combination codes have higher complexity compared with other coding methods, making the decoding process more intricate.

Applying differential pulse position modulation (DPPM) for encoding data offers robustness because error correction techniques can be employed, and the relative position of pulses is utilized to overcome synchronization difficulties in the decoding process [30]. During the channel transmission of mud pulse signals, data can be erased and the probability of erasure increases with transmission distances increasing. Traditional error correction codes (ECC) and automatic repeat request (ARQ) solutions are not well suited for MPT. Zhang et al. [31] proposed a raptor codes transmission (RCT) scheme based on raptor codes. This scheme compresses raw data using differential pulse code modulation (DPCM) and employs short-length raptor codes, demonstrating good erasure resistance to ensure real-time and accurate transmission of logging data. In addition, information can be encoded into pulse signals using other methods such as non-return-to-zero (NRZ) [4] and pulse width modulation (PWM) [32].

For CW-MPT systems, data undergoes coding and digital modulation before being transmitted to the surface in the form of continuous pressure waves via the passband. The coding methods used in CW systems are similar to those used in positive pulse systems, and the modulation techniques commonly employed include three common ASK, FSK, and PSK, as well as relatively novel techniques such as orthogonal frequency-division multiplexing (OFDM) and trellis-coded modulation (TCM). The modulation of mud pulse signals is a kind of mechanical modulation process [33]. It involves changing the motor speed to alter the flow rate of drilling mud passing through the valve within a unit of time, thereby generating pressure wave signals. Due to the influences of load torque and system inertia, instantaneous changes in motor speed are difficult to achieve, resulting in mechanical inertia. Therefore, it is necessary to develop robust and reliable modulation techniques suitable for MPT systems by improving traditional modulation techniques from the field of conventional communications or combining different techniques.

OOK is a special case of ASK modulation. Xu et al. [34] conducted numerical simulations to analyze the relationship between SNR and bit error rates of a mud pulse telemetry system based on OOK modulation in a 3000 m deep well. The feasibility of this approach was demonstrated. However, the pressure wave signals generated based on ASK modulation, including OOK, can experience irregular amplitude changes due to various noise interferences, such as mud pump noise, resulting in a high receiving bit error rate and a decrease in the reliability of system communication performance. FSK modulation can be easily achieved by directly controlling the motor’s rotation frequency to change the signal frequency. However, FSK modulation requires a large bandwidth and is challenging to achieve higher transmission rates. PSK modulation, on the other hand, offers good noise resistance and high reliability [21], making it suitable for signal transmission in complex well-site environments. PSK modulation includes BPSK and higher-order modulation schemes such as QPSK and 8PSK [35].
Although, theoretically, higher modulation orders result in faster transmission rates, simply increasing the modulation order to improve communication rates presents challenges for generating ideal waveforms with mud pulse signal generators. Moreover, higher-order PSK modulation has smaller minimum phase unit changes (e.g., $\pi/4$ for 8PSK), which can make demodulation difficult due to the small phase being vulnerable to complex noise interference. So, QPSK is a well-established and widely used modulation technique. Offset quadrature phase shift keying (OQPSK) is an improved constant envelope modulation technique based on QPSK. It offsets the two signal paths by half a symbol period in time. Compared with QPSK, OQPSK avoids the problem of complex frequency transitions in mud pulse signal generators caused by $180^\circ$ phase shifts. Additionally, OQPSK offers the same data transmission rate and bit error rate as QPSK under the same signal power and bandwidth conditions [36]. To overcome the issue of undesirable signal waveform caused by the difficulty of abrupt changes in the rotating valve speed, Wu et al. [37] proposed a continuous phase frequency keying (CPFK) technique. This approach allows for precise control of waveform generation while ensuring smooth rotation of the valve. The modulated signals are smoother and more suitable for transmission through the channel, facilitating easier recognition at the receiving end. Simulation results showed that the data transmission rate for continuous waves reached 15 bits/s, with a bandwidth utilization of 1 Baud/Hz.

TCM combines modulation and coding techniques, allowing for increased data transmission rates without additional bandwidth requirements [38], which can improve the communication performance of MPT systems. For example, combining the excellent error correction capability of TCM with the bandwidth-saving effect of 8PSK modulation can maximize system performance, reducing the bit error rate in low SNR environments and obtaining additional coding gain [35,39]. By combining TCM with pulse interval modulation (PIM), significant coding gains can also be achieved by maximizing the minimum time distance between modulated output sequences [40]. OFDM modulation has good bandwidth utilization and can effectively overcome multipath fading issues. However, it is sensitive to orthogonality between subcarriers and susceptible to inter-carrier interference (ICI) and ISI. Currently, OFDM modulation is relatively complex and less commonly used in MPT systems, but it has potential for development. Berro et al. [4] studied a novel approach called hybrid mud pulse telemetry (HMPT), which utilizes the mud channel to transmit both baseband and passband signals in parallel. In HMPT, the mud siren is used to transmit the passband signal, while the pressure pulser is used to transmit the baseband signal, operating in their independent transmission slots. Water circulation experimental results showed that although the data transmission rate increased by only 10% to 30%, this approach combining baseband and passband transmission provides a new direction for mud pulse signal transmission methods.

4. Research on Mud Channel Characteristics

The mud channel is an essential component of MPT communication systems. During the transmission process, the mud pulse signal will be distorted by various factors, which increases the difficulty of signal recognition and processing at the surface. However, there are still some ambiguous and even contradictory conclusions regarding the signal transmission mechanism such as the mud channel model. Therefore, further study of the transmission mechanism of mud pulse signals is still needed to look for a better mathematical description method [41].

4.1. Mud Channel Modeling

The MPT channel is a parameter-unknown, continuously varying, and highly unreliable time-variant channel [31]. Constructing an accurate channel model is beneficial for better understanding the channel characteristics and the impact of the mud channel on the signals. This enables the correct and appropriate design of mud pulse transmitters and receivers, thereby improving the communication performance of the MPT system.
The following Lamb formula is often used to predict the attenuation model of mud pulse signals in the drill string [42,43]:

\[ P(x) = P_0 e^{-x \sqrt{2 \eta \omega / d}} \]  

(1)

where \( P_0 \) is the reference pressure at zero distance, \( d \) is the inner diameter of the mud channel, \( \omega \) is the angular frequency of the signal, \( \eta \) is the viscosity of the mud, and \( v \) is the mud flow velocity, and \( P(x) \) is the pressure of the signal after propagating the distance \( x \). Equation (1) indicates that the amplitude of the mud pulse signal exponentially decays with increasing transmission distance. However, this model only describes the attenuation characteristics of the signal and does not consider dispersions caused by reflections, thus it cannot fully simulate the propagation process of mud pulses. Liu et al. [41] proposed a mathematical model based on the Allievi equation, which establishes a relationship between pressure and time distance, and provides specific differential equations and general solutions. The differential equation is

\[
\begin{align*}
\frac{\partial H'}{\partial x} + \frac{1}{gA} \frac{\partial Q'}{\partial t} + \frac{2fQ_0Q'}{gDA^2} &= 0 \\
\frac{\partial H'}{\partial t} + \frac{a^2}{gA} \frac{\partial Q'}{\partial x} &= 0
\end{align*}
\]  

(2)

where \( H' \) is the variation of the hydraulic head, \( Q' \) is the variation of the quantity of flow, \( Q_0 \) is the invariant of the quantity of flow, \( a \) is the wave velocity, \( A \) is the cross-sectional area, \( D \) is the inner diameter of the drill pipeline, \( x \) is the longitudinal distance of the pipeline, and \( t \) is the time. Via simulation of the model, it can be observed that the pressure wave signal is distributed in a standing wave pattern. As the signal frequency increases, the amplitude does not attenuate linearly but exhibits periodic attenuation characteristics with many peaks.

In recent years, more sophisticated electric transmission line theories have been used to study the transmission characteristics of pressure waves in drill pipelines [44]. An infinitesimal section of a fluid transmission line is shown in Figure 5. The pressure waveform at position \( x \) and time \( t \) of the mud pulse signal, \( P(x) \) in Pascals, is equivalent to a voltage waveform and the mass flow waveform, \( Q(x) \) in kg/s, is equivalent to current [42]. Han et al. [45] established an integrated model of the mud pulse pressure wave signals and pipelines based on transmission line theory. They also proposed a grid coupling division process, which provides a reliable and efficient research model for studying the optimization, reflection, and attenuation of pressure wave signals. Nath et al. [42] utilized distributed transmission line theory and fluid simulations of transmission line components to establish the first model characterizing the frequency selectivity of mud pulse channels. This model takes into account the influence of pipeline connection nodes and the impedance mismatch caused by the connection of end-of-drill string equipment, and it can effectively predict signal attenuation and reflection within the drill pipeline. Jia et al. [46] considered the influence of boundary layer thickness on viscous friction and the effect of pipeline materials on characteristic impedance and proposed a frequency-domain transfer function model for mud pulse channels based on the 2D Navier–Stokes equations and distributed transmission line theory. This model is suitable for analyzing the attenuation, superposition, and dispersion caused by multipath reflections in low-frequency and high-frequency mud pulse signals.

4.2. Fading and Multipath Propagation

During the propagation of mud pulse signals in the drill pipeline, power loss occurs due to the viscous dissipation and friction of the borehole wall, which is influenced by various factors such as well depth, mud viscosity, mud density, signal frequency, drill pipeline diameter, the number of drill pipeline sections, and annular clearance [46,47].
The mud fluids have high viscosity, and when combined with other high-concentration leakage substances, they can cause significant signal energy attenuation under long-distance transmission conditions [3]. Moreover, different frequency ranges of the signal experience varying different attenuation degrees, with higher frequencies suffering more severe attenuation. Advanced MPT systems often use higher frequencies for data transmission, which can further exacerbate the signal attenuation [48,49]. High-frequency components are more attenuated than low-frequency components, causing different frequency components of the signal to propagate at different speeds, and the time-domain signal will be smeared, resulting in signal dispersion. Therefore, it is possible to lower the carrier frequency appropriately, reduce mud viscosity by raising the mud temperature [46] or injecting nitrogen, and employ more advanced signal processing techniques to mitigate signal attenuation and improve the SNR of the received signal.

Mud pulse signals experience reflections at the nodes of mud pipelines, vibration dampeners, mud pumps, and drill bit connections due to impedance mismatch caused by the change in pipeline diameter, material, and structure [48]. These different transmission line segments have different instantaneous impedances. When there is a significant change in instantaneous impedance, the signal propagates in different directions, with a portion continuing forward and a portion reflecting back as echoes, resulting in multipath propagation. In the drilling system, there are only a limited number of multipaths that have a great impact on mud signal transmission. If the multipaths with less energy are ignored, it can be considered that there are six effective multipaths in the typical multipath system depicted in Figure 6 [21]. Multipath propagation leads to asynchronous reception of symbols at the surface, causing ISI and severely degrading the quality of the received signal. Additionally, the superposition of the main wave and multiple echoes causes destructive interference [50], resulting in severe signal attenuation and a low SNR at the surface. Equalizers are commonly used to overcome multipath propagation and compensate for signal distortion, and they are a key technology in surface signal processing. They will be discussed in more detail later.

4.3. Noise Analysis

Noise is generally considered to be anything other than the desired target information. Mud pulse signals are affected by a significant amount of noise during transmission in the communication channel. The amplitude of the noise is greater than that of the pulse signal, and its frequency spectrum partially overlaps with the signal, resulting in a low SNR of the transmitted signal. Therefore, separating the noise from the received signal and obtaining a high SNR signal becomes a challenging and crucial task in surface signal processing. Conducting thorough research on the types and characteristics of noise present in the channel helps in employing more accurate and scientific methods to filter out noise. To better study the impact of noise on the signal, special training sequences (TS)
can be transmitted, and then the received waveform at the surface is compared with the transmitted waveform to estimate channel distortion [51].

![Diagram](image)

**Figure 6.** Reflection characteristics of mud pulse signal when the pipeline diameter of drill string changes.

Noise that affects mud pulse signals includes mud pump noise, reflection noise, bottom-hole mechanical vibrations, drill string vibrations, electromagnetic interference, pulse noise, and mud friction [52,53]. Among them, mud pump noise is the largest noise source. It is a periodic noise signal with a regular pattern, while other noises can be considered non-periodic random Gaussian white noise. Generally, the transmission model for mud pulse pressure waves can be described in Figure 7.

![Diagram](image)

**Figure 7.** Schematic diagram of the MPT signal transmission model.

The data transmission formula can be described as follows:

$$ r(t) = s(t) * h(t) + p(t) + w(t) $$

(3)

where $s(t)$ is the original mud pulse signal, $p(t)$ is the mud pump noise, $w(t)$ is random Gaussian white noise, $r(t)$ is the signal collected by the pressure sensor, $h(t)$ is the impulse response function (IRF) of the channel, and $*$ means convolution. The output result of
the downhole signal via the channel is the convolution of the channel IRF $h(t)$ and the signal $s(t)$.

The mud pump is a device that provides power to the mud, and the pressure sensor on the surface is installed close to the mud pump, making the mud pump a strong noise source. When the mud pump operates under stable conditions, the pump noise is a relatively stable periodic signal, with a fundamental frequency that remains fixed and corresponds to the frequency of the mud flow discharged by the pump. Unfortunately, the operating state of the mud pump is often unstable, and therefore the pump noise is not entirely periodic. The pump noise includes the fundamental frequency component and multiple distinct harmonic components, and its spectrum is distributed in a comb shape. If the mud pump speed or the number of cylinders changes, the frequency of the pump noise will change accordingly. Mud pumps usually adopt reciprocating triplex pumps, the cyclic angular variation of the mud flow is $2\pi/3$ [54]. Therefore, the mathematical model of mud pump noise can be simply regarded as a periodic signal composed of the superposition of three sinusoidal signals with different frequencies as follows [55]:

$$p(t) = a\sin(2\pi f_{p1}t) + b\sin(2\pi f_{p2}t + \frac{\pi}{3}) + c\sin(2\pi f_{p3}t + \frac{2\pi}{3})$$

(4)

where different types of mud pump noise can be simulated by adjusting the coefficients $a$, $b$, and $c$.

However, there is currently no fixed and accurate mathematical model that describes the characteristics of mud pump noise. The pump stroke signal, which describes the parameter information of the reciprocating motion of the pump piston can be detected by using a pump stroke sensor [56]. Yang et al. [57] attempted to estimate the channel impulse response function of the pump stroke signal using the coherent accumulation method and established a Longuet-Higgins probability distribution for the pump stroke frequency to model the pump noise using statistical methods. Chen et al. [58] constructed three pump noise models applicable to ordinary n-cylinder mud pumps under normal operation: linear time-invariant, linear time-varying, and nonlinear models. The energy of the pump noise is relatively high, causing the mud pulse signal to be submerged in the pump noise. Therefore, the denoising of pump noise has always been a focus and challenge in surface signal processing. The other random Gaussian white noise has less energy and is easy to handle, so it will not be analyzed too much.

5. Surface Signal Processing of the Mud Pulse Signal

As mentioned in the previous section, the mud channel is subject to complex and severe noise, which significantly interferes with the signal quality and increases the difficulty of signal detection and extraction at the surface. Therefore, the main objective of surface signal processing is to restore the telemetry data as perfectly as possible. Surface signal processing mainly includes signal denoising, channel equalization, signal synchronization, and decoding.

5.1. Signal Noise Cancellation Techniques

Noise cancellation techniques can be divided into classical filters and modern filters based on the types of digital filters used. Classical filters, such as low-pass, high-pass, bandpass, and bandstop filters, eliminate out-of-band noise to obtain the desired signal. However, in the case of mud pulse signals, there is often an overlap between the signal and noise frequency bands. Therefore, the use of classical filters alone may not achieve satisfactory denoising results, necessitating the use of modern filters. Modern filters include adaptive filtering, wavelet transform, empirical mode decomposition (EMD), and Kalman filtering. These filters optimally extract the signal from the noise based on certain statistical distribution rules within the random signal.
5.1.1. Wavelet Transform

The Fourier transform has the advantage of reflecting the frequency components of a signal over the entire time range, making it suitable for processing stationary process signals. However, it has obvious limitations when dealing with non-stationary processes because it can only capture the overall frequency components of a signal segment, without providing information about the frequency characteristics at each moment. In the case of non-stationary mud pulse signals with the frequency varying over time, the multi-resolution property of the wavelet transform is more suitable for denoising purposes [26,52].

The wavelet transform replaces the infinite-length trigonometric basis functions in the Fourier transform with finite-length and decaying wavelet basis functions, providing a more refined representation of signals. The continuous wavelet transform is defined by the expression [59] as follows:

$$CWT(\alpha, \tau) = \frac{1}{\sqrt{|\alpha|}} \int_{-\infty}^{+\infty} f(t) \psi^* \left( \frac{t - \tau}{\alpha} \right) dt$$

(5)

where

$$\psi_{\alpha,\tau}(t) = \frac{1}{\sqrt{\alpha}} \psi \left( \frac{t - \tau}{\alpha} \right)$$

(6)

is called the wavelet basis function. It is a two-dimensional basis in the space obtained by scaling and shifting the mother wavelet $\psi(t)$. $\alpha$ is the scale parameter, $\tau$ is the translation parameter, and $^*$ means conjugate. The scale $\alpha$ controls the stretching of the wavelet function, while the translation $\tau$ controls its shifting. The selection of wavelet basis, scale parameter, and vanishing moments significantly affects the denoising performance. There is no unique wavelet basis function, so different wavelet basis functions should be chosen based on the characteristics of the actual signal in practical applications. For example, the earliest proposed Harr wavelet has good time-domain localization properties; the LP wavelet has good frequency-domain localization properties; the Meyr wavelet performs well in both time and frequency domains with fast convergence; the db wavelet has good regularity for smooth signal reconstruction, and there are also various other wavelet basis functions such as bior, coif, sym, mech, morl, etc. The scale parameter $\alpha$ is the most important parameter in wavelet transform. A smaller scale provides a narrower effective width for the wavelet, resulting in a higher time-domain resolution suitable for high-frequency signal processing. Conversely, a larger scale provides a wider effective width for the wavelet, resulting in higher frequency-domain resolution suitable for low-frequency signal processing [53]. The vanishing moments represent the concentration of energy after wavelet transformation. The higher the vanishing moments, the smaller the wavelet coefficients in the high-frequency band, and the flatter the corresponding filters, leading to a better approximation of smooth signals. However, the trade-off is that it requires more computation and longer processing time.

Namq et al. [60] proposed a method for the recognition of non-stationary mud pulse pressure wave signals based on the continuous Morlet wavelet transform. The continuous Morlet wavelet transform allows for adjustable window sizes with changing frequencies, enabling local refinement analysis of spatial frequencies. Simulation results demonstrated that using this method to process mud pulse signals with ASK and FSK modulation, it was possible to successfully distinguish the frequency components and corresponding time intervals of the signals, effectively eliminating random noise in MPT. Liang et al. [26] presented a wavelet transform algorithm for denoising high-speed mud pulse signals. By comparing the correlation degree, reconstruction capability, and SNR between the original and denoised signals, the optimal wavelet basis at different decomposition levels is determined. The feasibility of the proposed high-data-rate mud pulse system was verified via field experiments. Aiming at the random noise in the reconstructed mud pulse signal, Chen et al. [58] proposed a wavelet threshold denoising method based on a new power threshold function. Simulation results showed that combining the standard
Kalman filtering method with the power wavelet denoising algorithm achieved optimal overall performance for a linear time-invariant pump noise model. When applying the proposed approach to process actual deep well mud pulse signals, the ideal downhole pulse transmission waveform is successfully reconstructed.

5.1.2. Adaptive Filtering

The adaptive filter is a time-varying digital filter designed to provide the optimal output. It can automatically adjust the filter coefficients at the current time based on the previously obtained filter parameters, to achieve optimal filtering when the input signal or external noise changes. Figure 8 shows a typical diagram of an adaptive filter, which consists of a parameter-adjustable digital filter and an adaptive algorithm. Among them, \( x(n) \) is the input signal containing noise; \( y(n) \) is the output signal; \( d(n) \) is the desired signal; and \( e(n) \) is the error signal. The basic working principle of the adaptive filter is to continuously and adaptively adjust the current filter coefficients according to the error signal value via a certain adaptive algorithm such as LMS or RLS so that the output signal \( y(n) \) is infinitely close to the desired signal \( d(n) \) [51].

![Figure 8. Schematic diagram of the adaptive filter.](image)

Adaptive algorithms have been a research focus in the field of signal processing, widely applied in noise removal and channel equalization. Shen et al. [61] investigated the theoretical method of using the LMS algorithm in an adaptive filter to dynamically remove noise from pressure PSK-modulated mud pressure wave signals. The research results showed that selecting an appropriate adaptive filter step size factor can improve the SNR of the reconstructed signal and reduce signal distortion. Moreover, under the same filtering step size factor conditions, the quality of reconstructed QPSK signals was better than that of DPSK signals, indicating that QPSK signals have stronger interference resistance. Liu [62] conducted a detailed analysis of the noise characteristics in drilling sites and proposed an adaptive Least Mean Square (LMS) iterative algorithm. This algorithm can adaptively eliminate noise and enhance the ability of the EM-MWD receiver to extract weak signals from a large amount of field noise. Experimental results demonstrated that the proposed LMS algorithm had fast convergence speed, small steady-state error, and small mean square error, making it suitable for both the EM-MWD and the MPT system for noise removal. Yan et al. [63] proposed an adaptive mud pulse noise cancellation system based on an improved variable step size LMS algorithm to overcome the interference of pump noise with harmonic frequencies close to the signal. The proposed LMS algorithm is compared with four LMS algorithms: LMS algorithm, NLMS algorithm, Wirch algorithm, and correlation. The results showed that the improved variable step size LMS algorithm achieved faster convergence speed and better filtering performance, improving the system’s interference resistance in the case of continuously changing interference noise frequencies.

5.1.3. Differential Noise Cancellation Algorithm with Dual Sensors

Single-pressure sensor methods have been widely applied due to their advantages of simplicity, reliability, and low cost. However, the effect is not as good when dealing
with complex pump noise. Compared with a single pressure sensor, the noise cancellation approach based on dual pressure sensors has shown excellent performance in eliminating complex and time-varying pump noise and has become the mainstream development direction for CW signal pump noise cancellation.

As shown in Figure 9, Sensor I is located near the wellhead, while Sensor II is near the mud pump. The uplink pressure wave signal is transmitted from Sensor I to Sensor II. Simultaneously, the pump noise propagates from Sensor II to Sensor I. Therefore, the signal and pump noise have different propagation directions, resulting in a phase transmission delay in the detected signals by the sensors. By applying phase shifting and cancellation techniques to solve the delayed differential equations, the effective signal can be extracted [64]. The use of a pulsation damper in the figure can reduce and disperse the impact energy of each piston in the mud pump, thereby reducing the vibration noise caused by impacts and smoothing the pressure wave signal [65].

![Figure 9. Schematic diagram of the MPT system with two pressure transducers.](image)

The pump noise cancellation method based on dual sensors has received significant attention from researchers, but some theoretical issues still need to be addressed urgently. Firstly, the time delay between the two sensors is closely related to their distance, so how to choose the best installation position and interval of dual sensors has an important impact on the signal extraction performance [49]. Shen et al. [66] pointed out that the distance between the two pressure sensors can be determined by analyzing the highest frequency of the pulse signal and the minimum wave speed. Yan et al. [54] conducted simulation experiments to analyze the denoising effect of the delay differential algorithm under different pump noise conditions and provided an ideal installation interval for the dual sensors. This algorithm also achieved satisfactory results in handling actual pump noise. Secondly, in the process of reconstructing the signal, it is necessary to capture the response characteristics between the sensors. However, the response characteristics can change with external conditions, and the ability to accurately construct the channel transfer function between the sensors affects the quality of the extracted signal. Qu et al. [67] adopted an adaptive filter based on the RLS algorithm to track the channel response characteristics between the dual sensors in real time and optimize the transfer function. In the 3000 m real-well test, the 12–24 Hz carrier BPSK modulation method was used, and it was observed that the main components of the pump noise were reduced by 49–92%, further confirming the excellent performance of using dual pressure sensors to suppress pump noise.

5.1.4. Empirical Mode Decomposition

Different from the Fourier transform or wavelet transform, EMD is a method that can decompose any input signal into multiple intrinsic mode functions (IMFs) without the need to predefined any basis functions. These IMFs are arranged in descending order of frequency,
containing useful signals and noise in different frequency ranges [68]. EMD is essentially a process of smoothing the signal, making it advantageous in analyzing non-stationary and nonlinear signals.

To overcome the problem of mode aliasing, Zheng et al. [69] proposed an improved ensemble empirical mode decomposition (EEMD) algorithm suitable for drilling mud pulse signal decomposition and noise removal. By testing 10 low-pass filtering algorithms constructed with different IMFs, the best algorithm combination was obtained. Zhong et al. [70] improved the time-varying filtering empirical mode decomposition (TVFEMD) performance and robustness by selecting the optimal TVFEMD parameter combination using the particle swarm optimization (PSO) algorithm. They also used permutation entropy as an evaluation criterion in the IMF component reconstruction process, which is more in line with practical engineering. Qu et al. [56] proposed an MPT pump noise cancellation method based on EMD-PSO. The approach involves decomposing the pump noise into a series of IMFs and residue signals using EMD, reconstructing the pump noise by selecting optimal weights via the PSO algorithm, and subtracting the reconstructed pump noise from the original signal to obtain a relatively clean initial signal. The feasibility of the proposed algorithm was tested via field experiments.

Compared with EMD, variational mode decomposition (VMD) has advantages in handling end effects and mode mixing problems. Jiang et al. [71] proposed a constant center frequency VMD (CVMD) algorithm for addressing pump noise in CW-MPT systems. This method sets the center frequency of traditional VMD as a constant value based on the primary frequency of the useful signal and the harmonic frequencies of the pump noise, which can adaptively decompose complex and time-varying signals. Analysis of actual field data processing showed that even under unstable pump noise conditions, the CVMD algorithm can effectively ensure the high quality of the useful signal and demonstrate excellent denoising performance, thus having strong engineering application values.

5.1.5. Deep Learning

In recent years, deep learning has achieved remarkable success in various fields such as computer vision, autonomous driving, speech recognition, and AI dialogue systems. By training models on large datasets, deep learning enables models to have powerful learning capabilities and demonstrates robust performance in practical applications. As a result, many deep learning-based techniques have been applied in wireless communications, including signal modulation and demodulation, noise reduction, and channel estimation and detection. This subsection will introduce the latest applications and prospects of deep learning methods in noise removal for mud pulse signals, providing a new approach for mitigating mud pump noise.

Yang et al. [57] proposed a mud signal denoising network (MSDnNet) based on convolutional neural networks (CNN). Simulation experiments showed that MSDnNet can extract mud pulse signals under different noise levels and significantly improve the SNR, demonstrating that the network has good generalization ability for mud pulse noise removal. Li et al. [72] formulated the continuous wave mud pulse signal denoising problem as a supervised sequence-to-sequence regression problem and proposed a novel approach using a bidirectional convolutional long short-term memory neural network (Bi-ConvLSTM). To achieve better noise removal performance, a pre-training dataset was created by adding pump noise and Gaussian white noise to signals. Experimental results showed that the model effectively suppressed the noise in the validation set samples, and both the SNR and correlation coefficient of the signals were significantly improved. Stochastic resonance technology, a technique widely used in weak signal detection in certain nonlinear systems, has shown excellent performance in signal processing applications. Zhang et al. [73] applied stochastic resonance technology to eliminate low-frequency noise in mud pulse signals in complex noise backgrounds. To address the parameter selection problem in the stochastic resonance model, an adaptive genetic simulated annealing algorithm was used to
determine the optimal parameters. Field experiments verified that this method can improve the SNR of mud pulse signals and achieve signal detection under low SNR conditions.

The noise suppression of mud pulse signals using deep learning methods is still in the preliminary exploration stage and faces two main challenges. Firstly, training powerful neural network models requires a large amount of training data, which makes it difficult for most researchers to obtain actual samples from different wellsites. Secondly, most proposed methods have only been validated via laboratory simulations and lack field testing. The actual wellsite noise is more complex, harsher, and has time-varying characteristics. Therefore, there is a higher requirement for the generalization and stability of the constructed models, leaving significant research space for further investigation.

5.2. Channel Equalization

As analyzed earlier, the mud channel exhibits frequency selectivity, meaning that the mud pulse signal experiences attenuation as the transmission distance increases, with higher frequencies suffering more severe attenuation. Additionally, the signal is subject to multipath propagation and time delay spread, resulting in severe ISI and higher bit error rates. Therefore, it is necessary to use equalizers to compensate for the received signal, mitigate the ISI caused by channel distortion [14], and improve the performance of MPT applications.

Equalizers are essentially adjustable filters and can be classified into time-domain equalizers and frequency-domain equalizers based on different domains. Time-domain equalizers work based on the time-domain response waveform, replacing the response waveform with ISI with a waveform without ISI to compensate for symbol time delay and reduce or even eliminate ISI. Frequency-domain equalizers are more intuitive as they directly estimate and compensate for the fading signal using the frequency characteristics of adjustable filters. Time-domain equalizers can be further classified into linear and nonlinear equalizers based on the presence of feedback adjustment. Linear equalizers do not involve closed-loop feedback adjustment, making them simple and easy to understand. However, they have higher noise intensity compared with nonlinear equalizers. The linear transversal equalizer is a common example of a linear equalizer. Nonlinear equalizers, on the other hand, make use of feedback decisions to adjust current parameters, and the decision feedback equalizer (DFE) is the most commonly used and effective nonlinear equalization method. DFE can adaptively compensate for distortions caused by multipath fading, improve symbol decision reliability, and address imperfect sampling synchronization issues [17]. DFE operates in two stages: training and tracking feedback. In the first stage, DFE obtains the optimal filter coefficients by minimizing the error between a special training TS and the equalizer output. In the second stage, the trained DFE mimics the distortion caused by the mud pulse channel to compensate for the signal and actively adjusts the coefficients based on the current signal to minimize the bit error rate [8,38].

5.3. Synchronization and Decoding

After denoising and equalization processing, an ideal waveform of the mud pulse signal can be obtained. The signal consists of a sequence of consecutive symbol sequences, so to demodulate and decode the signals, it is necessary to know the starting and ending times of the symbol sequences. However, signal attenuation and drilling noise can cause synchronization loss between the downhole encoder and surface decoder [74]. The use of synchronization technology can ensure the reliability of information transmission and improve the performance of the MPT system.

One effective method is to insert a known synchronization header sequence with distinct autocorrelation function characteristics before each data frame during downhole information coding. This header sequence serves to identify the start of a data frame. During surface decoding, the received signal is correlated with a predefined synchronization header template. The received signal exhibits the maximum amplitude and strongest correlation only at the position of the synchronization header. By setting a threshold, when
the correlation peak exceeds the threshold, it is determined as a valid correlation peak, indicating the start position of a frame. When the correlation peak is below the threshold, it is considered an invalid peak [75]. Barker code, which is a non-periodic sequence with special rules, is commonly used for frame synchronization in communication systems [26]. However, the synchronization header does not contain valid information, and a long synchronization header would introduce unnecessary overhead. Therefore, when determining the duration of the synchronization header, a trade-off between accuracy and efficiency should be considered. Traditional peak detection algorithms based on cross-correlation only utilize a single template signal. If two peak pulses are stacked too closely, the traditional method may mistakenly identify them as a single peak pulse, leading to false peak information. Lee et al. [76] proposed a multi-template cross-correlation stacking suppression method. This algorithm utilizes two overlapping peak pulses as a template signal, enabling effective detection of normal peak pulses even when the interval between two peaks is quite small.

In many cases, a fixed threshold value is pre-set to save on technical costs. When the amplitude of the detected signal exceeds the predetermined threshold, the corresponding pulse signal segment is considered to contain valid information. However, as analyzed earlier, the mud channel is harsh, and the signal strength attenuates during transmission. Relying solely on a fixed threshold value may result in problems such as false detection or missed detection of information.

Therefore, in order to increase the confidence of the decoding results, an adaptive modulation threshold is adjusted based on the actual signal. Hua et al. [29] proposed an adaptive dual-threshold method for mud pulse recognition. This method sets a small fixed threshold value and a dynamically adjusted adaptive threshold value. The small fixed threshold value filters out most of the interference noise, while the adaptive threshold value is determined and adjusted in real-time based on the recent three pulse peaks, effectively identifying the pulse signal. In a field test conducted in a 2000 m well, the pulse recognition error rate using this method was only 0.003%, significantly improving the robustness of the downhole communication system. Liu et al. [55] applied the image segmentation concept to the recognition of one-dimensional pulse signals, using the OTSU algorithm to obtain an adaptive threshold for the signal. In the signal processing neighborhood, the OTSU algorithm divides the signal into different intervals according to certain rules and searches for the optimal global threshold within these intervals, achieving recognition of the pulse signal. After accurately defining the starting time of the symbol, the modulated signal needs to be demodulated. To avoid signal spectrum overlap during demodulation, coherent demodulation is typically performed on narrowband signals [32]. The received symbol waveform is then compared with a reference waveform using modal similarity measurement and local feature recognition algorithms to identify the specific symbol information [77].

In addition, to improve the effectiveness of signal recognition, machine learning-based signal recognition methods have been proposed. Zhang et al. [78] applied wavelet neural networks and autoencoders to mud pulse signal recognition, proposing a deep learning-based stacked wavelet autoencoder (SWAE) method. Experimental results showed that after training the SWAE model with a large number of typical mud pulse signals, the model improved the output signal’s SNR and automatically recognized and classified mud pulse signals based on their features. Qu et al. [79] applied supervised classification machine learning models in the field of mud pulse pressure wave signal detection, constructing a PSO-SVM method for demodulating mud pulse pressure wave signals. They also expanded the training dataset with correctly demodulated data to improve the demodulation accuracy of the signals. Field test results demonstrated that the PSO-SVM approach with an expanded training set achieved demodulation accuracy of around 98% in the well over 2500 m, confirming the superiority of this approach.
6. Conclusions

Over the past few decades, the continuous development of downhole wireless communication technologies, represented by MPT, has improved the efficiency, safety, and economy of drilling operations. The MPT system is a typical communication system, and a reliable, high-speed, and user-friendly communication system relies heavily on robust communication links and advanced signal processing algorithms. Therefore, this review focuses on analyzing the coding and modulation of source signals; discusses existing mud channel models and their differences; analyzes signal attenuation, multipath propagation, and noise interference in mud channels; summarizes key factors to improve system communication performance in ground signal processing techniques such as noise cancellation, equalization, and synchronization.

With the gradual increase in drilling productivity, the MPT technology is facing more and more new challenges and has great room for development. The future development direction of MPT mainly has the aspects as follows:

1. Noise, especially pump noise, seriously affects the communication performance of the MPT system. Currently, the differential noise cancellation algorithm using dual sensors is an effective method for dealing with pump noise and holds research value. Moreover, since noise characteristics vary across different well sites, it is imperative to investigate advanced noise reduction algorithms in the future. For instance, a combination of deep learning, compressed sensing, and traditional adaptive filtering techniques should be explored. New algorithms possess the capability to learn from different wellsite noises, ultimately achieving exceptional denoising outcomes.

2. Traditional MPT systems often employ a single modulation scheme. In the future, combining different modulation schemes can be utilized to adapt to varying drilling conditions, enhancing data transmission rates and drilling efficiency.

3. Improving and optimizing the mechanical structure of downhole signal generators and control strategies for motors can enhance the quality of mud pulse signals, thereby increasing the efficiency and stability of the entire communication system.

4. Deep exploration and development of oil and gas resources constitute a crucial part of probing the Earth’s deep layers. Therefore, deep and ultra-deep wells will be vital directions for the future development of drilling technology. For deep or ultra-deep wells, the key lies in overcoming various challenges posed by high temperatures and pressures.

It is foreseeable that the MPT systems will rapidly evolve towards digitization, automation, integration, and intelligence. Researchers and practitioners worldwide are still delving further into challenges and solutions for MPT systems to improve drilling safety, reliability, efficiency, and economic benefits.

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