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Research on High-speed Digital Circuit Signal Transmission and Noise Suppression

Bowen Tan[1,*], **Zhiqi Hao**[2]

[1]Apple Inc., Cupertino, CA 95014, USA.
[2]Northwestern University, Evanston, IL 60208, USA.

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[*]**Corresponding author:** Bowen Tan, Apple Inc., Cupertino, CA 95014, USA.

Abstract

With the continuous advancement of semiconductor technology and integrated circuits, high-speed digital circuits are being applied more extensively. Leveraging their high-speed and high-density signal transmission capabilities, these circuits play a pivotal role in modern communication, computing, control, and other domains. However, as signal transmission speeds escalate, signal quality and integrity have emerged as focal points of concern. In the design of high-speed digital circuits, the presence of noise exerts a significant impact on signal transmission quality, becoming a key factor that restricts the enhancement of circuit performance. Researching signal transmission and noise suppression techniques in high-speed digital circuits holds great significance for improving circuit performance and ensuring stable system operation. Based on an understanding of the fundamental theories of high-speed digital circuit signal transmission, this paper analyzes the types and sources of noise in high-speed digital circuits and further explores noise suppression techniques and methods, aiming to enhance signal transmission performance and ensure the stable operation of the system.

Keywords

High-speed digital circuits; Signal transmission; Noise analysis; Noise suppression

In the process of high-speed signal transmission, noise issues have become increasingly prominent due to various factors, severely restricting the quality and efficiency of signal transmission. At present, although many studies have been devoted to solving this problem, noise suppression in high-speed digital circuits still faces many challenges. Therefore, it is necessary to deeply analyze the noise characteristics in the signal transmission of high-speed digital circuits and explore effective noise suppression technologies and methods, providing useful references for research and practice in related fields.

1. Basic Theories of High-speed Digital Circuit Signal Transmission

High-speed digital circuit signal transmission involves complex theories of electrical signals and electromagnetic fields. In high-speed transmission, signal integrity is a core consideration, influenced by various factors such as transmission line effects, dielectric loss, impedance mismatches, signal reflection, and crosstalk. The rise time and propagation delay of signals become critical parameters that determine the quality of the signal during transmission [1]. At the same time, the attenuation and dispersion effects of high-frequency signals must be carefully considered to avoid signal distortion. Moreover, high-speed signal transmission requires a deep understanding of electromagnetic compatibility to minimize the impact of electromagnetic interference on signal quality. To ensure the stability and reliability of signals, it is necessary to comprehensively apply transmission line theory, microwave transmission theory, and principles of electromagnetic compatibility to build an efficient and low-noise high-speed digital circuit signal transmission system.

2. Types and Sources of Noise in High-speed Digital Circuits

In the design and operation of high-speed digital circuits, noise has always been a key factor affecting the quality of signal transmission. As the operating frequency of the circuits increases and the level of integration grows, the sources and types of noise become more complex and diverse. Noise can not only lead to signal distortion and transmission errors but can also severely impact the stability and performance of the entire system. Therefore, a thorough understanding and analysis of the types and sources of noise in high-speed digital circuits are crucial for optimizing circuit design and improving signal transmission quality [2]. Specifically, the types of noise in high-speed digital circuits mainly include the following categories:

2.1 Electromagnetic Interference Noise

In high-speed digital circuits, rapid changes in current can generate strong electromagnetic fields, which may interfere with surrounding electronic devices and circuits through radiation or induction. The sources of electromagnetic interference noise are widespread, such as high-frequency signals in circuits, switching actions, and the external electromagnetic environment. This type of noise is characterized by its fast propagation speed and wide impact range, making it one of the key factors to consider in the design of high-speed digital circuits [3].

2.2 Power Supply Noise

As the energy source for the circuit, the stability and purity of the power supply are crucial for circuit performance. However, in practical applications, the power supply is often affected by various factors, such as power grid fluctuations and high-frequency harmonics from switching power supplies, resulting in power supply noise. This noise can propagate through the power lines to the entire circuit, causing interference with signal transmission [4]. Therefore, in the design of high-speed digital circuits, effective measures must be taken to suppress power supply noise and ensure the stability and purity of the power supply.

2.3 Signal Reflection Noise

When a signal encounters impedance mismatch during transmission on a line, reflection occurs, producing reflection noise. This noise can lead to signal waveform distortion, energy loss, and transmission delays, and in severe cases, may even cause circuit oscillation. To avoid the impact of signal reflection noise, it is necessary to properly plan the layout of transmission lines and impedance matching in circuit design, ensuring smooth signal transmission [5].

In addition to the above main types of noise, other types of noise such as thermal noise and shot noise may also exist in high-speed digital circuits. Although these types of noise are relatively small, they can significantly affect circuit performance under certain conditions. Therefore, in the design and optimization process of high-speed digital circuits, various noise factors must be considered comprehensively, and comprehensive suppression measures must be taken to ensure the stability and reliability of signal transmission.

3. Noise Suppression Techniques and Methods in High-speed Digital Circuits

3.1 Electromagnetic Interference (EMI) Suppression

In high-speed digital circuits, rapid changes in current and voltage fluctuations can cause electromagnetic field radiation and induction, resulting in electromagnetic interference (EMI). This interference can affect not only the internal signal transmission within the circuit but also potentially disturb surrounding electronic devices. Therefore, it is essential to reduce the generation of electromagnetic radiation and induction at the source. Shielding technology is a very effective method for suppressing electromagnetic interference. By using metal shielding covers or shielded cables, the electromagnetic field within the circuit can be confined to a certain area, preventing it from radiating outward or inducing external electromagnetic fields. The key to shielding technology lies in ensuring the integrity and continuity of the shield body to provide effective electromagnetic isolation. A reasonable shielding design also needs to consider the transmission requirements of signals and the layout constraints of the circuit, ensuring that shielding does not impede the normal transmission of signals and avoids unnecessary electromagnetic coupling with other parts of the circuit, to achieve optimal shielding effects. At the same time, adding appropriate filters to signal or power lines is also an important method to reduce electromagnetic interference. Filters can effectively filter out high-frequency noise components, allowing certain frequencies of signals to pass through selectively while blocking others, thereby reducing the propagation of electromagnetic interference. The selection and design of filters need to be considered comprehensively based on the operating frequency of the circuit, the characteristics of signal transmission, and the type of noise. For example, high-pass filters or band-rejection filters can be chosen for high-frequency noise, while low-pass filters can be selected for low-frequency noise. Parameters such as the bandwidth, stop-band attenuation, and pass-band ripple of the filter also need to be optimized according to specific requirements. The installation location and connection method of the filter will also significantly affect the filtering effect. Typically, filters should be installed near the signal source or load to minimize losses and reflections on the transmission line. The input and output ends of the filter should be correctly connected to avoid introducing additional noise and interference. In addition, optimizing the layout and routing of the circuit is key to reducing electromagnetic interference. By reasonably planning the routing of the circuit board, the layout of components, and the handling of ground lines, such as using multi-layer routing, increasing the width of ground lines, and using ground planes, electromagnetic coupling and induction within the circuit can be reduced, thereby decreasing the generation of electromagnetic interference. For example, increasing the spacing between signal lines, reducing the length of parallel routing, and using differential signal transmission can effectively reduce crosstalk and electromagnetic interference [5]. Differential signal transmission simultaneously transmits two signals with opposite phases, and at the receiving end, common-mode noise and interference are eliminated by subtraction, improving the signal's resistance to interference. Furthermore, for the power supply part of high-speed digital circuits, special attention should also be paid to the suppression of electromagnetic interference. As the energy source of the circuit, the stability and purity of the power supply are crucial to the performance of the circuit. Power supply noise and interference not only affect the normal operation of the circuit but can also propagate through the power lines to other devices, causing greater impact. To suppress electromagnetic interference in the power supply, voltage regulation measures can be taken. For example, using voltage regulator diodes, inductors, capacitors, and other components to form a voltage regulation circuit, using power supply filters to filter out high-frequency noise and interference on the power lines, and optimizing the power distribution network to reduce losses and reflections on the power lines, to lower the impact of power supply noise and electromagnetic interference on circuit performance.

3.2 Power Supply Noise Suppression

In high-speed digital circuits, suppression of power supply noise is crucial for ensuring the stable operation of the entire system. Power supply noise can affect the integrity of signals and may lead to decreased circuit performance, logical errors, or even system failure. Therefore, it is particularly important to adopt effective techniques and methods for power supply noise suppression. Power supply noise mainly originates from the instability of the power supply itself and various factors in the power distribution network (PDS), such as the impedance of power lines, electromagnetic induction, and load variations. To suppress this noise, it is essential to start with the power supply design. High-quality power supply modules should be selected, which typically have lower noise and higher stability. Additionally, using appropriate voltage regulation circuits and filtering circuits is indispensable to reduce power supply output ripple and noise. For example, low-noise linear regulators (LDOs) or switching regulators (DC-DC) can be used, and filtering capacitors and inductors can be added to their output to further reduce noise [6]. In terms of the power distribution network, a reasonable layout and routing are key to suppressing power supply noise. The loop area between power lines and ground lines should be minimized to reduce noise generated by electromagnetic induction. By increasing the width of power lines and ground lines, their impedance can be reduced, thereby lowering the attenuation of noise during transmission. Using a multi-layer PCB design, separating the power and ground layers, can also effectively improve the suppression of power supply noise. This design can reduce coupling between the power and ground layers, thus reducing the propagation of noise. Moreover, decoupling technology is an important means of suppressing power supply noise. Decoupling capacitors provide a low-impedance path to absorb high-frequency noise in the circuit. When selecting decoupling capacitors, parameters such as their capacitance, voltage rating, and ESR (equivalent series resistance) should be considered to ensure they can work effectively within the target frequency range. Decoupling capacitors should be placed close to the power pins and the length of the trace between them and the power pins should be minimized to avoid forming excessively long traces or loops that could affect the decoupling effect. For switching power supplies in high-speed digital circuits, due to their higher operating frequencies, they are more prone to generating power supply noise. Therefore, when using switching power supplies, special attention should be paid to noise suppression measures. For instance, appropriate filters can be added to the input and output of the switching power supply to filter out high-frequency noise. At the same time, optimizing the control strategy of the switching power supply, such as adopting soft-switching technology, can also effectively reduce the noise it generates. Soft-switching technology involves controlling the turn-on and turn-off processes of the switch, reducing the rate of change of voltage and current during switching, thereby lowering switching noise.

3.3 Crosstalk Suppression

In high-speed digital circuits, crosstalk is an issue that cannot be ignored, as it arises from electromagnetic coupling between signal lines, Crosstalk not only affects the integrity of the signal but can also lead to logic errors and performance degradation. Therefore, employing effective crosstalk suppression techniques and methods is crucial for ensuring the stable operation of high-speed digital circuits. Specifically, it is important to deeply understand the mechanisms behind the generation of crosstalk. In high-speed digital circuits, rapid changes in signals cause rapid changes in electromagnetic fields, which are transmitted between adjacent signal lines through mutual inductance and mutual capacitance, resulting in crosstalk. The magnitude of crosstalk depends on various factors, such as the spacing between signal lines, the length of parallel runs, the signal frequency, and the dielectric constant of the medium. To suppress crosstalk, one effective method is to reduce the coupling between signal lines through reasonable routing strategies. This includes increasing the spacing between signal lines, reducing the length of parallel runs, and using differential signal transmission, among others. For example, when designing circuit boards, one can consciously increase the distance between adjacent signal lines to reduce their electromagnetic coupling. Shortening the length of parallel runs can also effectively reduce the impact of crosstalk. Increasing the spacing between signal lines can reduce mutual inductance and mutual capacitance, thereby lowering crosstalk. Reducing the length of parallel runs can shorten the coupling path, further reducing crosstalk. Differential signal transmission, which involves transmitting a pair of signals with opposite phases, can cancel out external interference, including crosstalk, thereby improving the signal's resistance to interference. In practical applications, differential signal transmission is widely used in high-speed digital circuits, such as USB, HDMI, and other interface standards. In addition to routing strategies, shielding technology can also be used to suppress crosstalk. Shielding technology is a very effective method for suppressing crosstalk, as it prevents the propagation of electromagnetic fields by adding a metal shielding layer around the signal lines, thereby reducing crosstalk. Shielding layers can be grounded metal plates, metal meshes, or metal foils, among others. They can effectively absorb or reflect electromagnetic fields, containing crosstalk within the shielding layer and thus protecting external circuits from interference. For example, in high-frequency circuits, metal shielding enclosures are often used to cover the entire circuit or critical parts to reduce the interference from external electromagnetic fields. Furthermore, a reasonable ground wire layout and grounding method are also important means to suppress crosstalk. As the reference potential line in the circuit, the layout and grounding method of the ground wire will directly affect the noise and interference in the circuit, providing a low-impedance path. Ground wires can guide crosstalk currents back to the source, thereby reducing the impact on adjacent signal lines [7].

3.4 Reflection Suppression

In high-speed digital circuits, signal reflection is a common phenomenon that can lead to signal distortion, timing errors, and performance degradation. Reflections are primarily caused by impedance mismatches during signal transmission. When a signal propagates from one impedance region to another, if the impedances are not matched, part of the signal's energy is reflected back to the source, creating a reflected wave. This reflected wave combines with the original signal, altering its amplitude and waveform, and introducing noise. To effectively suppress reflections in high-speed digital circuits, attention must be paid to transmission line impedance matching. Impedance matching is key to ensuring that signals propagate from one circuit component to another without reflections. For example, when designing a high-speed digital circuit, if the characteristic impedance of the transmission line is 50 ohms, then the source and load impedances should also be designed to be 50 ohms to ensure impedance matching. Properly designing the transmission line impedance to match the source and load impedances can significantly reduce signal reflections, which typically involves precisely controlling parameters such as the width, thickness, dielectric constant, and termination resistors of the transmission line [8]. In practical applications, termination resistors are a common means to suppress reflections. For instance, in high-speed interfaces like PCIe, a resistor matching the characteristic impedance is often added at the end of the transmission line to absorb the reflected energy and reduce the impact of the reflected wave on the signal. The value of the termination resistor needs to be determined based on the characteristic impedance of the transmission line to ensure the best impedance-matching effect. The layout and connection method of the termination resistor also needs careful consideration to avoid introducing additional parasitic effects. In addition to impedance matching and termination resistors, other techniques can be used to further suppress reflections. For example, differential signal transmission technology uses a pair of signals with opposite phases to cancel out the effects of reflected waves. Differential signal transmission is widely used in high-speed digital interfaces such as USB and HDMI, which not only reduces reflections but also enhances the signal's resistance to interference. Furthermore, using appropriate buffers or drivers can also reduce reflections during signal transmission. These devices have low output impedance and high driving capability, which better match the transmission line impedance, thereby reducing reflections. Additionally, for complex circuit systems, more advanced reflection suppression techniques, such as Time Domain Reflectometry (TDR) measurements and simulation analysis, may be required. TDR technology can accurately measure impedance changes and reflections in transmission lines, providing strong support for optimizing impedance matching. For example, during the circuit board production process, TDR technology can be used to detect whether the transmission line impedance is matched and if there are any reflection issues. Simulation analysis, on the other hand, can predict and assess the impact of reflections on circuit performance during the design phase, guiding designers to make targeted optimizations. For instance, at the early design stage, simulation software can be used to model and analyze the circuit, predict the impact of reflections on signal integrity, and optimize the design based on the simulation results.

3.5 Synchronous Switching Noise (SSN) Suppression

In high-speed digital circuits, Simultaneous Switching Noise (SSN) is a type of power noise generated by multiple circuit elements switching states simultaneously. This noise can cause fluctuations in the power supply voltage, which in turn affects the stability and performance of the circuit. To effectively suppress SSN, a series of specialized techniques and methods must be adopted. First and foremost, optimizing the Power Distribution Network (PDN) design is the cornerstone of suppressing SSN. The PDN, as a collection of power, ground planes, decoupling capacitors, etc., is crucial for the selection of its layout and parameters. For instance, when designing a high-speed digital circuit, we can increase the thickness of the power plane and choose materials with a smaller dielectric constant to reduce the impedance of the power plane, thereby decreasing the amplitude of SSN. Proper planning of the power plane routing to avoid long power lines that cause increased impedance is also an important aspect of optimizing PDN design [9]. Secondly, employing decoupling capacitor technology is an effective means to suppress SSN. Decoupling capacitors provide a low-impedance path to quickly absorb high-frequency noise in the circuit. When selecting decoupling capacitors, parameters such as their capacitance, voltage rating, equivalent series resistance (ESR), and equivalent series inductance (ESL) must be considered comprehensively. For example, for a circuit with a high operating frequency and significant noise, we should choose decoupling capacitors with larger capacitance and smaller ESR and ESL to ensure they work effectively within the target frequency range. Additionally, the layout of the decoupling capacitors must be particularly cautious, placing them as close to the noise source as possible to reduce the length and inductance of the connecting lines, thereby enhancing the decoupling effect. Furthermore, employing Electromagnetic Bandgap (EBG) structures is an innovative method for suppressing SSN. EBG structures can introduce periodic resonant cavities in the power plane, cleverly preventing the propagation of electromagnetic waves within a specific frequency range. This structure not only significantly reduces the propagation of SSN in the power plane but also lowers its impact on the circuit. For example, in a high-density packaged circuit, EBG structures can be introduced to suppress the power noise inside the package, thereby improving the stability and performance of the circuit. Improving signal transmission technology is also a crucial approach to suppressing SSN. Differential signal transmission, as an advanced signal transmission method, cleverly cancels out external interference, such as SSN, by transmitting a pair of signals with opposite phases. This transmission method not only enhances the signal's resistance to interference but also reduces the coupling between signal lines, further lowering the impact of SSN. For instance, differential signal transmission is widely used in high-speed digital interfaces such as USB, HDMI, etc., to ensure the integrity and stability of the signal. Additionally, reasonably selecting the width and spacing of signal lines is key to reducing the impact of SSN. Wider signal lines and appropriate spacing can reduce the mutual inductance and mutual capacitance effects between signal lines, thereby lowering the coupled noise of SSN. Finally, considering the design and operating environment of the entire circuit system is an important aspect of suppressing SSN. In practical applications, it is necessary to select and optimize SSN suppression techniques and methods based on the specific conditions of the circuit. For example, for high-density packaged circuits, special attention should be paid to the suppression of power noise inside the package; for circuits with high-speed data transmission, it is essential to focus on improving signal integrity and anti-interference capabilities.

4. Conclusion

In summary, the study of signal transmission and noise suppression in high-speed digital circuits is an important topic in the field of modern electronic technology. With the continuous development of technology, the performance requirements for high-speed digital circuits are also increasing, and noise is one of the key factors limiting their performance enhancement. By analyzing the basic theories of signal transmission in high-speed digital circuits, the sources and types of noise are thoroughly explored, and corresponding suppression techniques and methods are proposed for different types of noise. These techniques and methods cover various aspects such as electromagnetic interference suppression, power supply noise suppression, crosstalk suppression, reflection suppression, and synchronous switching noise suppression, providing comprehensive theoretical support and practical guidance for the design and optimization of high-speed digital circuits. This effectively improves the signal transmission performance of high-speed digital circuits, ensures the stable operation of the system, and thus promotes technological progress and development in related fields.

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