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Experimental Research on Time Synchronization and Initiation at the Appointed Time for Wireless Electronic Detonator Initiation System

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Abstract: This paper proposes and experimentally validates a wireless electronic initiation system that achieves millisecond-level time synchronization and reliable detonation at a precisely scheduled moment. The system adopts a master-slave architecture based on LoRa wireless communication and the Precision Time Protocol (PTP), with embedded controllers running on STM32 and FreeRTOS platform. Unlike traditional systems that rely on real-time broadcast commands, this system employs a scheduled initiation strategy, whereby each slave device executes detonation autonomously at a pre-agreed time based on synchronized local clocks. This approach ensures high timing accuracy, improves safety by allowing pre-execution status checks of all devices, and eliminates risks associated with communication delays or interference. Experimental results confirm that the system consistently achieves sub-millisecond synchronization and precise, simultaneous initiation across multiple nodes, demonstrating its feasibility and robustness for use in complex blasting operations.

Keywords: Wireless Electronic Detonator; Wireless Initiation System; Time Synchronization; Initiation at the Appointed Time

1. Introduction

In recent decades, the explosive engineering industry has undergone a transformative shift from conventional wired initiation systems to advanced wireless electronic detonator initiation systems (Dozolme and Bernard T., 2005; Zhang, Xie and Jia, 2025) [1-3]. This transition is primarily driven by the demand for enhanced safety, operational efficiency, and the ability to execute precise, large-scale blasting operations in complex and hazardous environments (Dozolme and Bernard, 2006) [4-6]. Wireless initiation technologies offer substantial benefits, such as reduced setup time, minimized personnel exposure in blast zones, and greater flexibility in deployment. However, this evolution also introduces critical challenges—particularly in achieving precise time synchronization and reliable detonation at pre-scheduled times.

Traditional wired systems have long benefited from inherent timing stability due to direct electrical connections. In contrast, wireless systems rely on radio communication, which is inherently subject to transmission delays, interference, and synchronization drift (Zuraida *et al.*, 2018) [7-9]. For digital electronic detonators that often require millisecond-level accuracy, even minor deviations in synchronization can lead to suboptimal blast results, reduced safety margins, or, in worst-case scenarios, catastrophic failure.

A critical challenge in wireless blasting operations lies in ensuring precise and reliable timing synchronization across all initiation points, particularly when using a distributed master-slave architecture involving hundreds of detonators(Yang *et al.*, 2012; Idrees *et al.*, 2020) [10-12]. Addressing this challenge requires an integrated approach that combines robust communication protocols, real-time operating systems, high-precision synchronization algorithms, and fault-tolerant system design (Li *et al.*, 2020)[13-15].

This study presents an experimental investigation into a wireless initiation system that achieves millisecond-level synchronization and reliable detonation at a pre-defined time. The system is based on a cascaded master-slave architecture using LoRa (Long Range) wireless communication, Precision Time Protocol (PTP)-based time synchronization, and real-time embedded controllers built on FreeRTOS and STM32 platforms.

The main objectives of this research are:

− To evaluate the feasibility of using PTP in a wireless communication environment for time synchronization in blasting operations.

− To implement a scheduled detonation mechanism based on synchronized local clocks, eliminating the dependency on real-time trigger commands.

− To experimentally validate the timing accuracy and robustness of the system under various conditions, including signal attenuation and asynchronous start-up scenarios.

The remainder of this paper is organized as follows:

− Section 2 discusses the principles and technical foundations of wireless detonator systems, including communication technologies, synchronization mechanisms, and scheduled detonation strategies.

− Section 3 presents the hardware and software system design and implementation.

− Section 4 describes the experimental setup and results of synchronization and detonation tests.

− Section 5 summarizes the findings and proposes future directions for improving accuracy, resilience, and scalability in wireless initiation systems.

2. Principles of Wireless Detonator Systems

Wireless electronic initiation systems have revolutionized the field of blasting operations by eliminating the limitations associated with wired detonator networks (Cardu, Giraudi and Oreste, 2013) [16-18]. These systems enable more flexible deployment, enhanced safety for personnel, and support for precise timing control in complex environments. However, the transition from wired to wireless initiation introduces significant technical challenges—particularly in maintaining reliable communication, achieving high-precision time synchronization, and ensuring secure, scheduled initiation of multiple blasting units.

This chapter elaborates on the core principles underlying wireless electronic initiation systems, including an evaluation of wireless communication technologies, a description of time synchronization mechanisms, and the design methodology of scheduled initiation protocols.

2.1 Comparison of Wireless Communication Technologies and the Optimal Choice for Wireless Detonation Systems

Wireless communication is the backbone of modern initiation systems. In the context of explosive operations, communication links must be robust, secure, and capable of performing reliably in adverse environmental conditions such as underground mines, construction sites, and remote terrains. Table 1 presents a comparative analysis of commonly used wireless technologies, considering their frequency, range, interference resistance, power consumption, and key advantages and disadvantages:

Table 1. Comparison of Wireless Communication Technologies for Wireless Applications

Technology	Frequency Range	Transmission Distance	Interference Resistance	Power Consumption	Key Pros and Cons
LoRa (Long Range)	433MHz / 868MHz / 915MHz	Long range (1-15 km)	Strong	Low power	**Pros:** ●Long-range, ●Low power ●Strong resistance to interference **Cons:** ●Low data rate
Wi-Fi	2.4GHz / 5GHz	Short to medium range (up to 100m)	Medium	High power	**Pros:** ●High-speed data transfer, ●Easy to deploy **Cons:** ●Short range ●High power consumption
Bluetooth	2.4GHz	Short range (10-100m)	Medium	Ultra-low power	**Pros:** ●Low power

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					●Suitable for small devices **Cons:** ●Limited range ●Easily affected by interference
ZigBee	2.4GHz	Short range (up to 100m)	Strong	Low power	**Pros:** ●Low power ●Mesh network support **Cons:** ●Low data rate
NB-IoT	700MHz-900MHz	Long range (tens of kilometers)	Strong	Low power	**Pros:** ●Wide coverage ●Stable connectivity **Cons:** ●Dependent on telecom operators ●Higher cost
Satellite Communication	GHz range	Global coverage	Strong	High	**Pros:** ●Ultra-long range ●Unaffected by terrain **Cons:** ●Expensive ●High latency

Among these, LoRa is the most appropriate technology for wireless electronic initiation systems due to its balance of low power consumption, wide-area coverage, and independence from external infrastructure. Why LoRa is Preferred for Wireless Initiation Systems:

(1) Long-Range Transmission

LoRa enables reliable long-distance communication in both open areas (10-15 km) and challenging environments such as mountains, tunnels, and underground sites (1-5 km).

Compared to Wi-Fi, Bluetooth, and ZigBee, which are limited to short ranges, LoRa offers superior coverage without requiring extensive infrastructure.

(2) Excellent Interference Resistance

LoRa utilizes Chirp Spread Spectrum (CSS) modulation, which provides robust interference immunity.

This is especially beneficial in electromagnetically noisy environments, such as mines, construction zones, and military operations, where traditional Wi-Fi or Bluetooth signals may suffer from significant interference.

Compared to NB-IoT, which depends on cellular network infrastructure, LoRa operates independently, ensuring stable communication in remote areas.

(3) Low Power Consumption

LoRa devices have ultra-low power consumption, enabling battery-operated deployments that can last years without frequent recharging or maintenance.

Unlike Wi-Fi, which consumes a lot of power, LoRa's energy efficiency makes it ideal for long-term field operations.

(4) High Security and Data Encryption

Security is a crucial aspect of a wireless detonation system, as unauthorized access could lead to severe consequences.

LoRa supports AES-128 encryption and end-to-end authentication, ensuring that communication remains secure and protected against hacking or jamming.

(5) Cost-Effective & No Need for Cellular Networks

LoRa does not rely on telecom operators like NB-IoT or satellite communication, significantly reducing operational costs.

Compared to satellite communication, which is expensive, LoRa provides an affordable solution while still maintaining long-range capabilities.

In remote or military applications, where setting up cellular networks is impractical, LoRa offers an independent, self-sufficient communication solution.

In contrast, technologies such as Wi-Fi or Bluetooth are generally unsuitable due to limited range, higher power consumption, and susceptibility to signal degradation. Therefore, LoRa emerges as the optimal wireless technology for reliable, secure, and efficient detonation system communication.

2.2 Time Synchronization in Wireless Detonation Systems Using Precision Time Protocol (PTP)

Precise time synchronization is vital for electronic initiation systems, particularly in operations requiring coordinated multi-point detonations. Traditional wired systems benefit from shared physical clock references. In wireless systems, however, maintaining sub-millisecond synchronization is more complex due to signal latency and transmission variability.

The Precision Time Protocol (PTP), standardized as IEEE 1588, is employed to overcome these challenges (Zhao, Wang and Yang, 2011; Yuan, Guo and Tian, 2021)[19-22]. It provides sub-microsecond synchronization accuracy in distributed systems via timestamped message exchanges. PTP is designed to provide highly accurate time synchronization over a network, making it an ideal solution for wireless detonation systems. Unlike NTP (Network Time Protocol), which offers millisecond-level synchronization, PTP achieves nanosecond precision, ensuring that all detonators receive accurate timing signals for a perfectly coordinated explosion sequence.

PTP works by exchanging timestamped messages between a Master Clock and multiple Slave Clocks (detonation devices) to achieve precise synchronization.

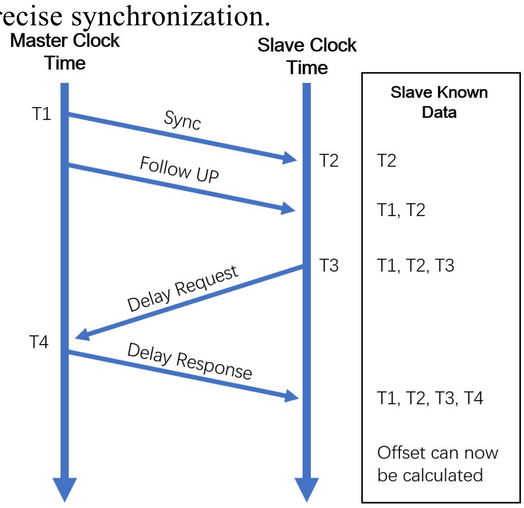

Figure 1. The Precision Time Protocol Synchronization Process

Figure 1 shows PTP Synchronization Workflow:

(1) Master Initiation Unit: broadcasts a Sync message to all slaves.

(2) Remote Initiation Devices: slaves record their local reception time T2.

(3) A Follow-Up message from the master provides a recorded T1 timestamp.

(4) Devices send a Delay Request T3; the master replies with T4.

(5) Each device calculates its time offset using:

$$Offset = \frac{[(T2 - T1) - (T4 - T3)]}{2} \quad (1)$$

(6) Remote devices then correct their internal clocks accordingly.

This process ensures that all initiation devices share a highly synchronized time base, allowing them to execute scheduled detonation events with precise alignment.

Challenges and Solutions in Implementing PTP in Wireless Networks:

Variable Wireless Latency: Use Transparent Clocks (TCs) in the network to measure and compensate for latency variations.

Packet Loss: Solved via message redundancy and acknowledgements.

Environmental Interference: Addressed through LoRa's modulation scheme and physical-layer resilience.

2.3 Scheduled Initiation Strategy

Scheduled wireless initiation system refers to the predefined execution of an explosion at an agreed-upon moment in time, rather than relying on a real-time command to trigger the detonation. Unlike traditional detonation methods that send an immediate detonation command, scheduled detonation systems transmit a detonation timestamp in advance. This timestamp is repeatedly sent to ensure all detonation units receive and store the agreed time before execution.

Since the system is built on a real-time operating system (RTOS) and has already achieved precise time synchronization across all devices, each unit can independently execute detonation at the exact agreed-upon moment. This eliminates command transmission delays and network uncertainties, ensuring that all charges detonate in perfect synchronization.

Basic Implementation of Scheduled Detonation

(1) Time Synchronization Across All Slave Units

Before initiating any detonation operation, a highly accurate time synchronization mechanism PTP is used to ensure that all detonators share a common time reference. This synchronization process compensates for network delays, ensuring each unit has identical timekeeping down to the microsecond level.

(2) Transmission of the Agreed Detonation Time

Instead of sending a direct detonation command, the control system transmits a detonation agreement message containing the exact time for the explosion. This message is transmitted multiple times to ensure all slave units receive and confirm the agreed timing before detonation.

(3) Pre-Arming and Verification

Upon receiving the agreed detonation time, each unit stores the precise time and enters a pre-armed state. The system continuously verifies that all slave units have successfully received and acknowledged the agreed time. If a unit fails to confirm, it can either request retransmission or trigger a fallback procedure.

(4) Execution at the Synchronized Time

Since all detonators are synchronized to the same time, they do not rely on a final trigger signal to detonate. Each unit monitors the synchronized clock and executes the detonation precisely at the pre-agreed moment, ensuring perfect coordination across all charges.

Advantages of Scheduled Detonation in Wireless Systems

Eliminates Communication Delays: Since detonation timing is pre-agreed, there is no dependency on real-time command transmission, eliminating risks from network latency, interference, or signal loss.

Ensures Synchronization Accuracy: By using PTP-based time synchronization, all detonation units execute at the exact same moment, ensuring consistent blast wave propagation and controlled explosion sequencing.

Enhances Reliability with Redundant Confirmation: The multiple transmissions of the detonation timestamp ensure that all units receive and confirm the timing, preventing failure due to lost messages.

−Improves Safety and Scalability: Operators can verify synchronization status before execution, ensuring all detonators are ready. This allows for large-scale, precise, and controlled detonation sequences in complex environments such as mining, tunneling, and demolition.

By integrating LoRa-based communication, PTP synchronization protocols, and autonomous scheduled initiation, wireless electronic initiation systems can achieve high-precision blasting in scalable, robust, and secure configurations. These principles form the foundation for the system implementation described in the next section.

3. System Design and Implementation

To meet the stringent requirements of modern blasting operations—such as precision timing, remote deployment, and high reliability—this study proposes a wireless electronic initiation system based on a hierarchical master-slave control architecture. The system integrates embedded microcontrollers, LoRa wireless communication, and a Precision Time Protocol (PTP)-based synchronization framework. It is designed to support millisecond-level timing precision across multiple initiation controllers distributed over a wide area.

This section outlines the system architecture, hardware configuration, communication protocol, and synchronization strategy adopted in the implementation.

3.1 System Architecture Overview

The proposed system employs a cascaded master-slave topology, where a central master initiation controller manages synchronization, timestamp distribution, and command control, while multiple slave controllers' interface directly with electronic detonators and execute the scheduled initiation events.

Each slave controller manages dozens to hundreds of initiation channels, and multiple slave units can be chained to support large-scale blasting operations. Figure 2 illustrates the overall system topology.

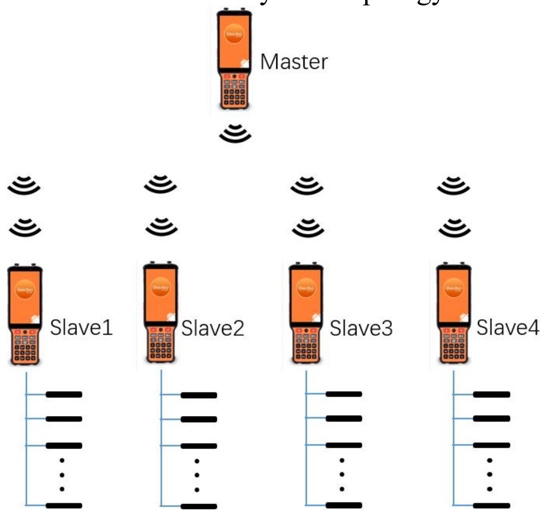

Figure 2. Topology of the Cascaded Wireless Electronic Initiation System

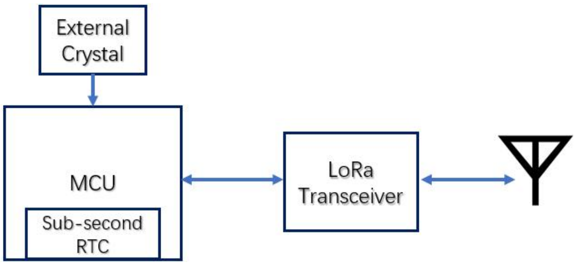

Figure 3. Hardware Block Diagram of the Initiation Controller Unit

In this configuration:

The master controller handles user interface, synchronization broadcasting, and detonation scheduling.

Slave controllers execute synchronization protocols and store scheduled detonation timestamps for localized execution.

This modular architecture enhances scalability, allowing the system to coordinate several hundred electronic detonators through distributed control.

3.2 Hardware Design

Figure 3 shows the Hardware Block Diagram of the Initiation Controller Unit. Both the master and slave initiation controllers are based on the STM32F407 microcontroller platform, which provides:

ARM Cortex-M4 core with sufficient processing capacity

Support for external high-accuracy crystal oscillators

Real-Time Clock (RTC) with sub-second register access

Integrated SPI/UART interfaces for LoRa module communication

To ensure timing accuracy:

An external 20 ppm or better crystal oscillator is used for each controller to minimize clock drift.

The STM32 RTC peripheral provides 1 ms resolution by dividing the second into 1,000 units, enabling microsecond-scale detonation scheduling.

The LoRa module (30 dBm output power) is used for robust wireless communication, offering a non-line-of-sight range exceeding 1.5 km in field tests.

Power-efficient design and low RF duty cycle further support long-term operation in harsh environments using battery power.

3.3 Real-Time Operating System and Synchronization Mechanism

The control software for both master and slave units runs on FreeRTOS, a lightweight real-time operating system (RTOS) that ensures deterministic task execution. FreeRTOS enables:

High-priority interrupt handling for synchronization messages

Timely execution of the PTP protocol stack

Non-blocking delay management during pre-arming and alarm setup

Time synchronization between the master and slave controllers is achieved using a customized implementation of PTP, adapted for LoRa-based packet transmission. Since the STM32 RTC sub-second registers are read-only, direct modification is infeasible. Instead, the slave controller computes the time offset from the master and applies it to future timing calculations without altering its local clock.

The synchronization process includes:

(1) Initial PTP session during system startup

(2) Offset calculation and storage at each slave controller

(3) Final PTP synchronization immediately prior to detonation

This ensures that time drift remains within acceptable limits (less than 1 ms) and enables precise coordination for initiation at scheduled timestamps.

The system uses a customized command protocol over the LoRa link to handle:

Device registration and status queries

Time synchronization exchanges (Sync, Follow-Up, Delay Request, Delay Response)

Detonation timestamp broadcasting

Device readiness confirmation and fault acknowledgment

To improve robustness:

All critical messages are sent redundantly.

Devices respond with acknowledgments and enter retry loops in case of transmission failure.

If a slave device fails to confirm synchronization or timestamp acceptance, the master initiates a fallback procedure to halt the detonation process.

This built-in fault detection mechanism ensures system safety and operational integrity in case of device malfunction, wireless signal degradation, or environmental interference.

3.4 Software Flow for Scheduled Initiation

Figure 4 illustrates the software logic flow in the master controller, detailing the sequential operations for synchronization, timestamp distribution, and execution of scheduled detonation.

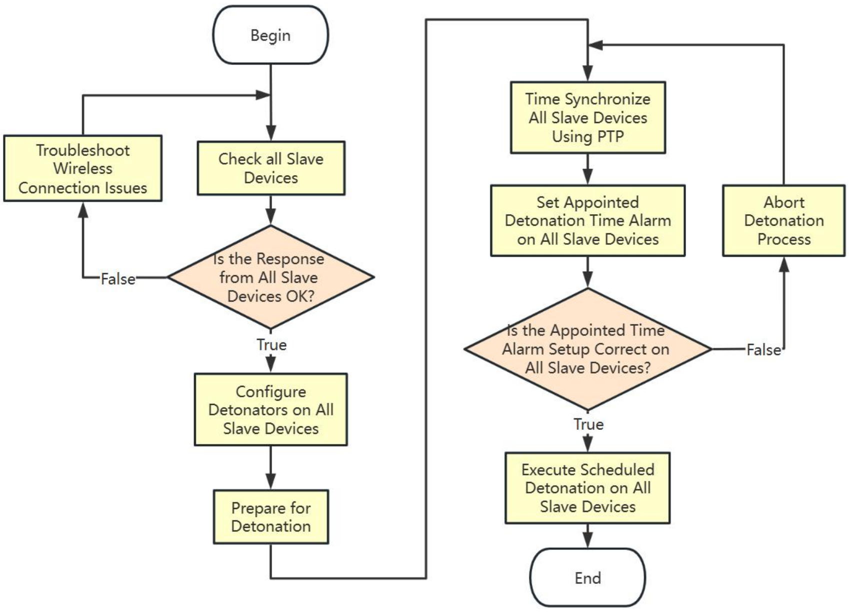

Figure 4. Software Flowchart for Synchronization and Scheduled Initiation

Key stages include:
Device discovery and status validation
Configuration of detonation parameters
Execution of PTP-based time synchronization
Broadcast of detonation timestamp and multi-pass confirmation
Final verification of timestamp reception
Autonomous execution of detonation by each slave controller

The detonation is aborted if any slave controller reports failure in synchronization or timestamp configuration, ensuring the entire system operates only under verified and synchronized conditions.

By combining embedded real-time systems, long-range wireless communication, and precision synchronization, the proposed system provides a reliable and scalable platform for wireless electronic initiation. The following chapter presents experimental validation of the system under varying signal attenuation conditions and evaluates its timing accuracy.

4. Experimental Results

This section presents experimental validation of the key assumptions and functional performance of the proposed wireless electronic initiation system. The experiments focus on two major objectives:

(1) To validate the applicability of PTP in a wireless LoRa-based environment by verifying the assumption of symmetric transmission delay.

(2) To evaluate the actual detonation timing accuracy: achieved across multiple slave initiation controllers executing scheduled blasts.

4.1 Validation of Symmetric Transmission Delay for PTP Applicability

The Precision Time Protocol (PTP), standardized as IEEE 1588, is employed in this study to achieve time synchronization between the master and slave initiation controllers. A fundamental assumption of PTP is that the communication delay in both directions (from master to slave and vice versa) is approximately equal. This symmetric delay assumption underpins the calculation of clock offset between devices.

In wired networks, this assumption typically holds due to consistent transmission paths and minimal asymmetry. However, in wireless networks—especially those based on LoRa—this assumption may not naturally hold due to environmental noise, antenna mismatch, or hardware-related asymmetries. Therefore, validating this assumption is a necessary precondition before applying PTP to wireless synchronization.

Experimental Setup:

Two STM32-based initiation controllers were configured to communicate via LoRa modules using point-to-point wireless links.

Both devices were placed in close physical proximity to allow simultaneous observation via a single high-precision oscilloscope, which measured the relative signal timing.

Instead of physically increasing the distance, attenuators (10 dB, 20 dB, 30 dB) were inserted inline to simulate signal degradation corresponding to different distances or transmission loss.
Bidirectional transmission delays were measured by triggering identifiable signals in each direction and observing the propagation delay difference between devices.

Results and Interpretation:
In all configurations in Table 2, the delay variation between the two transmission directions remained within ±0.25ms, with total discrepancies under 0.6ms. These results confirm that the symmetric delay assumption holds sufficiently well for PTP application in the proposed LoRa-based wireless environment.

Table 2. Bidirectional Transmission Delay Measurements

Number	Device A		Device B		Time Delay (ms)
1	Transmit	10dB	Receive	10dB	49.490
2	Transmit	10dB	Receive	20dB	49.598
3	Transmit	10dB	Receive	30dB	49.486
4	Transmit	20dB	Receive	30dB	49.532
5	Transmit	30dB	Receive	30dB	49.386
6	Receive	10dB	Transmit	10dB	49.400
7	Receive	10dB	Transmit	20dB	49.320
8	Receive	10dB	Transmit	30dB	49.574
9	Receive	20dB	Transmit	30dB	49.580
10	Receive	30dB	Transmit	30dB	49.604

Sample oscilloscope traces for selected test cases (Figures 5 and 6) visually demonstrate the minimal offset between bidirectional transmissions.

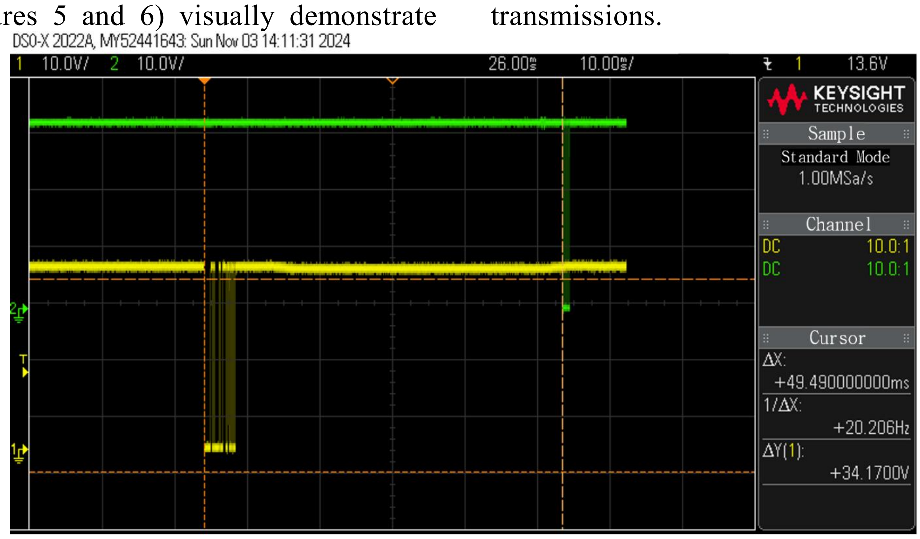

Figure 5. Test Number 1 Result for A as Transmit Unit and B as Receive Unit

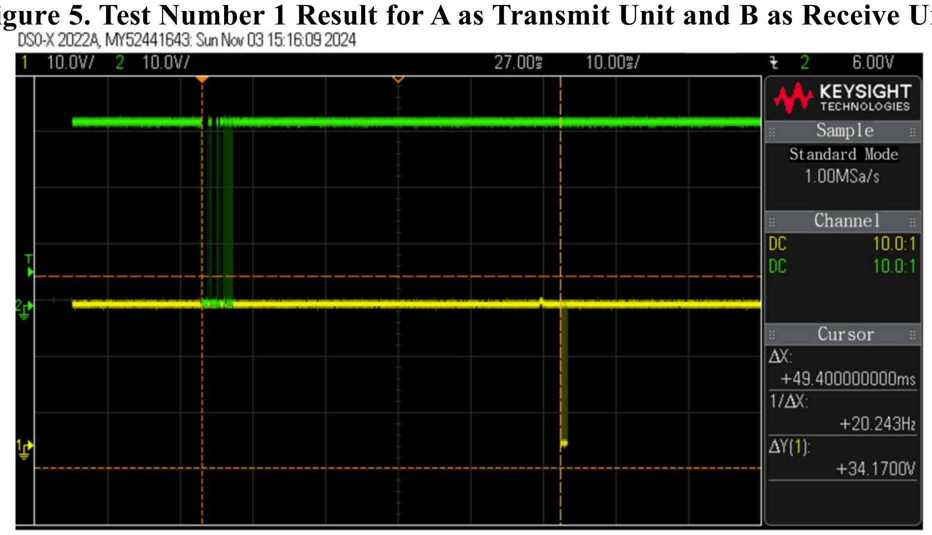

Figure 6. Test Number 6 Result for B as Transmit Unit and A as Receive Unit

Thus, the system meets the necessary precondition for accurate PTP-based time synchronization, establishing a foundation for subsequent experiments.

4.2 Verification of Scheduled Initiation Accuracy

After validating the delay symmetry required for PTP, the full initiation system was assembled to assess actual synchronization and scheduled detonation precision. The test is setup as follow:

The experimental network consisted of one master controller and four slave controllers, connected via LoRa in a star topology.

Upon initialization, all devices underwent PTP-based synchronization, and the master then broadcast a scheduled detonation timestamp.

Each slave device stored the timestamp locally and executed initiation autonomously based on its synchronized internal clock.

Pairs of slave devices were selected for timing comparison using an oscilloscope, under varying attenuation conditions to simulate different communication link qualities.

Table 3. Scheduled Initiation Timing Offset Between Slave Controllers

Number	Test Slave ID	Attenuation (dB)	Test Slave ID	Attenuation (dB)	Time Delay (ms)
1	1	10	2	10	0.200
2	1	10	2	20	0.780
3	1	20	2	20	0.160
4	1	10	3	10	0.220
5	1	10	3	20	0.660
6	1	20	3	20	0.300
7	2	10	4	10	0.010
8	2	10	4	20	0.560
9	2	20	4	20	0.420

Results and Analysis: from Table 3 data, the maximum observed offset between initiation events was 0.78ms, with most measurements falling below 0.5ms.

These results indicate that:

The synchronization process was successful in aligning device clocks within a sub-millisecond margin.

The scheduled initiation mechanism based on preloaded timestamps operated reliably and deterministically.

LoRa signal attenuation had a limited and consistent effect on the initiation timing accuracy, demonstrating the system robustness.

Figures below show oscilloscope captures for selected test results.

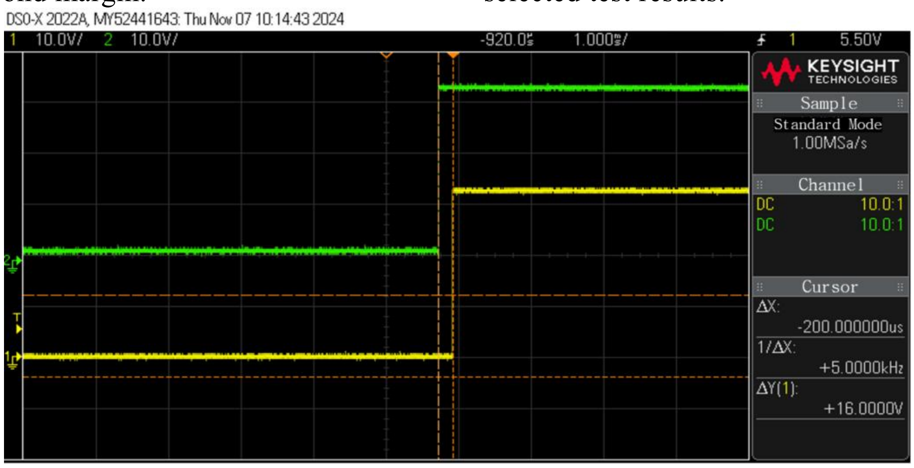

Figure 7. Test Number 1 Result

4.3 Discussion

The experiments confirm that the proposed wireless initiation system can support millisecond-level synchronization accuracy and reliable execution of scheduled detonation events under variable signal quality conditions. Key observations include:

The symmetric delay assumption holds within acceptable bounds for PTP to be applicable over LoRa links.

Scheduled initiation was executed within sub-millisecond offsets across distributed slave controllers.

Attenuation does not significantly degrade timing accuracy, indicating that the synchronization mechanism is resilient to common wireless link variations.

However, the tests were conducted under semi-controlled laboratory conditions with attenuators simulating field conditions. For full industrial deployment, further testing in real-world environments—such as underground mines, high-noise urban zones, or military settings—is recommended to verify system performance under multipath fading, temperature variation, and long-term oscillator drift.

In conclusion, the experimental results establish the viability of using PTP over LoRa for precise time synchronization in wireless electronic initiation systems. The combined architecture of synchronized distributed controllers and scheduled autonomous execution provides a robust and scalable foundation for modern blasting operations.

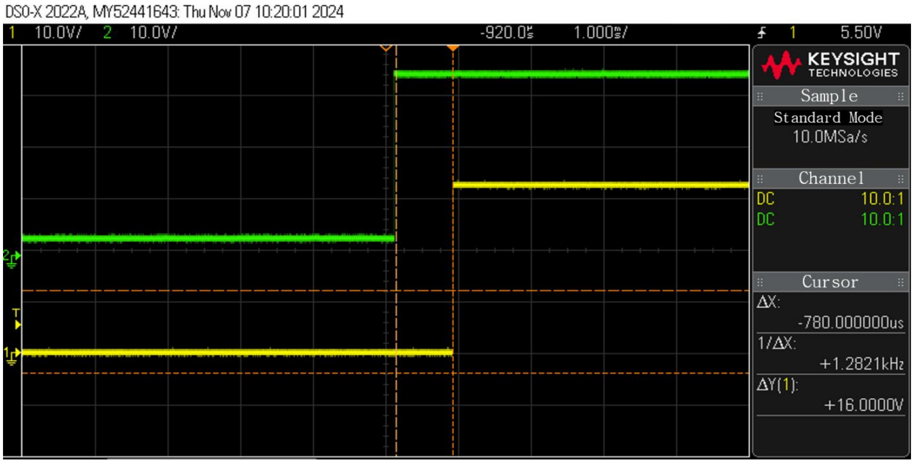

Figure 8. Test Number 2 Result

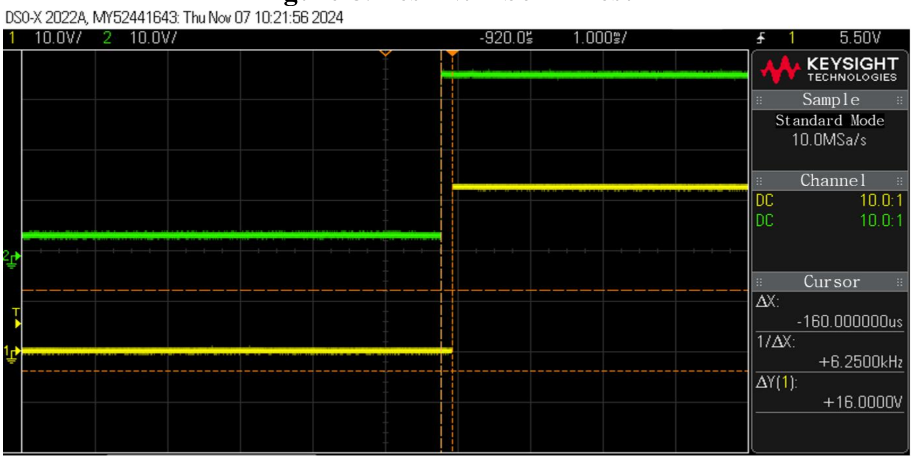

Figure 9. Test Number 3 Result

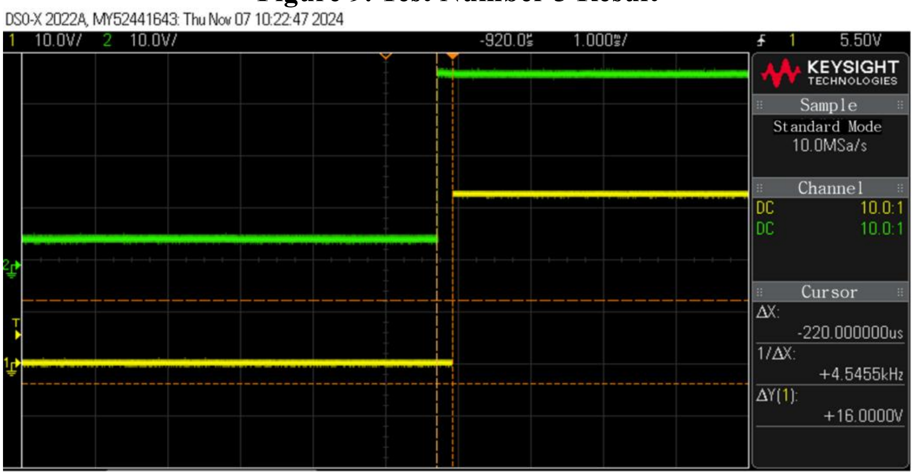

Figure 10. Test Number 4 Result

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5. Conclusions and Future Outlook

This study investigated the design and implementation of a wireless electronic initiation system that achieves high-precision, scheduled detonation method through the integration of LoRa-based communication, PTP-based synchronization, and real-time embedded controllers.

The system was developed using a cascaded master-slave control architecture, where a central master controller distributes synchronization signals and scheduled initiation timestamps to multiple slave units. All controllers were implemented on STM32 microcontrollers running FreeRTOS, enabling deterministic execution and low-latency response. LoRa wireless modules were selected for their long-range, low-power, and interference-resistant characteristics, making them suitable for remote and harsh blasting environments.

The research yielded the following major outcomes:

Validation of PTP Applicability in Wireless Environments: A dedicated experiment was conducted to evaluate the symmetric transmission delay assumption required for PTP operation. Results demonstrated that forward and reverse wireless delays over LoRa links remained within a ±0.3 ms range, confirming the protocol applicability.

Successful Implementation of Wireless Time Synchronization: The system achieved millisecond-level time alignment across all distributed initiation units. Offset between any two synchronized slave controllers was consistently within 1 ms, confirming the robustness of the PTP-based method in wireless communication environments.

Reliable Execution of Scheduled Detonation: By using preloaded timestamps and synchronized local clocks, the system executed fully autonomous detonation events. The maximum timing deviation observed across multiple devices was under 0.8 ms, meeting industrial precision requirements.

Fault Tolerance and Safety Measures: The initiation logic included redundancy in message delivery, pre-arm validation, and fallback abort mechanisms. These features ensured the system operated only under verified, synchronized conditions, enhancing safety and reliability.

Future research directions will focus on enhancing system precision, robustness, and deployment readiness:

(1) Sub-millisecond Synchronization

Explore enhanced synchronization protocols or hardware timestamping techniques (e.g., hardware-assisted PTP or GPS-disciplined oscillators) to achieve microsecond-level alignment.

(2) Field Deployment in Harsh Environments

Conduct long-term trials in underground mines, tunnel construction, or military operations to assess system behavior under real-world noise, interference, and terrain conditions.

(3) Fault-Resilient Mesh Architectures

Extend the communication topology from star or cascade to mesh networks for redundancy and self-healing capabilities, particularly in complex or obstructed deployment areas.

(4) Integration with AI-Based Predictive Monitoring

Incorporate machine learning models to analyze system health (e.g., clock drift trends, communication stability), enabling predictive diagnostics and proactive maintenance.

(5) Cybersecurity Hardening

Investigate and implement secure boot, encrypted firmware updates, and intrusion detection mechanisms to enhance resilience against malicious attacks in sensitive operations.

In conclusion, this research demonstrates that a wireless initiation system employing PTP-based synchronization and scheduled autonomous execution can reliably achieve millisecond-level detonation precision. The results support the system application in precision blasting scenarios across mining, demolition, and defense industries, and provide a promising platform for further development toward safer, smarter, and more scalable explosive control systems.

Acknowledgement

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