Resiliently Synchronizing SFN Networks: Combining Precise Time Signals from GPS and Longwave Radio Stations

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***Abstract*—This study presents a novel approach for enhancing the resilience of time synchronization in Single Frequency Networks (SFN), particularly within the context of digital terrestrial television broadcasting standards. It critically assesses the reliance on Global Navition Satellite Systems (GNSS) for SFN synchronization, identifying it as a potential single point of failure due to GNSS's susceptibilities, such as ephemeris errors, ionospheric delays, solar activity, and potential attacks that compromise signal accuracy and reliability. The paper explores the potential of eLoran, a system that was developed to provide resiliency for global navigational systems by complementing GNSS systems with ground-based time signal radio stations for trilateration. Development of a similar system is proposed advocating for a holistic approach that combines GNSS with existing terrestrial time signal radio station infrastructure to enhance SFN resilience against vulnerabilities.**

***Index Terms*—SFN, GNSS, eLoran, DVB-T, time synchronization**

I. Introduction

With single frequency networks evolving to meet ever-increasing throughput demands, the precision of timing synchronization becomes crucial for the network performance. The advent of Digital Video Broadcasting – Terrestrial (DVB-T) standard and their subsequent enhancements in DVB-T2 have significantly raised the bar for synchronization accuracy. These standards, employing orthogonal frequency-division multiplexing (OFDM) modulation, offer substantial data througput but also introduce strict requirements for transmission synchronization to prevent inter-symbol interference and optimize bandwidth utilization [1, 2]. Historically, GNSSs, such as GPS and GLONASS, have been the cornerstone for achieving this level of synchronization across the geographically distributed infrastructure of SFNs because other systems like Precision Time Protocol (PTP), while effective in certain contexts with consistent network latencies, like a localized data center, encounter scaling challenges over geographical expanses, rendering them unsuitable [3, 4]. However, the reliance on GNSS without any complementary or backup system introduces a range of vulnerabilities, including susceptibility to ephemeris errors, ionospheric delays, solar activities, and potential security threats like jamming and spoofing which are thoroughly assessed in the section II-A. These vulnerabilities not only compromise the integrity and reliability of broadcast services but also highlight a critical single point of failure within the synchronization framework of SFNs.

To mitigate similar risks in the context of global navigation, the eLoran system was developed as a terrestrial-based alternative to GNSS, designed to offer a robust solution to the single point of failure issue by providing a complementary source of timing signals usable for positional trilateration [5]. The approaches suggested by eLoarn are further reviewed in this paper in the section II-C.

Inspired by the principles of eLoran, this study explores the feasibility of leveraging terrestrial radio stations, specifically those managed by the Russian State Service for Time, Frequency, and Earth Rotation Parameters, alongside similar stations in Germany, the United Kingdom, and Japan [6]. These stations, characterized by their picosecond-precision in time signal dissemination, present a viable solution for enhancing SFN synchronization resilience and accuracy.

This paper proposes a hybrid synchronization model that integrates the precision of GNSS with the reliability of ground-based time signals. By examining fitness of the existing infrastructure and evaluating the potential of these terrestrial time signal sources, the study seeks to evaluate the scalability limitations inherent in ground-based systems and to outline effective algorithms for the detection and integration of these signals within the SFN synchronization framework. The exploration of this hybrid model provides a way for a strategic approach to safeguarding digital broadcasting networks against the multifaceted spectrum of threats impacting GNSS reliability.

II. Literature review

A. GNSS Vulnerabilities

The vulnerabilities of GNSS encompass a multifaceted array of challenges that significantly impact the accuracy and reliability of signal synchronization, crucial for the optimal operation of SFN. These vulnerabilities manifest through a variety of technical and natural phenomena. Technical issues such as ephemeris errors and time system inaccuracies can introduce significant discrepancies in positioning and timing signals [7]. Additionally, natural phenomena like ionospheric and tropospheric signal delays present unpredictable challenges, distorting the signals transmitted by satellites. The impact of solar activity further complicates this scenario, inducing additional signal interference and delays [8].

Moreover, GNSS vulnerabilities extend beyond natural and technical challenges, encompassing serious threats from intentional interference and attacks, such as jamming and spoofing. Jamming involves the disruption or obstruction of GNSS signal reception, while spoofing entails the broadcasting of false signals to mislead GNSS receivers. Instances of such attacks, including documented cases of GPS signal jamming by North Korea affecting South Korea, highlight the increasing prevalence and sophistication of these threats [9]. The low power of satellite-borne signals makes GNSS particularly susceptible to such attacks, underscoring the need for robust countermeasures.

SFNs, relying heavily on precise timing synchronization, are especially vulnerable to the ramifications of GNSS disruptions. These vulnerabilities spotlight the critical importance of developing and implementing alternative time signal acquisition methods to ensure higher levels of security and reliability in systems dependent on accurate time synchronization. Reference [10] underlines the serious consequences of GNSS interferences and attacks, advocating for the exploration and adoption of alternative approaches to bolster the resilience and reliability of such critical infrastructure. This necessitates a comprehensive understanding of GNSS vulnerabilities and a proactive approach to safeguarding SFN synchronization against the myriad of threats facing GNSS, ensuring the continuity and integrity of digital broadcasting services.

B. SFN Synchronization

Single Frequency Networks rely on the precise synchronization of broadcast signals across multiple transmitters to ensure seamless signal delivery to receivers within the network. This synchronization is crucial for preventing signal interference and maximizing network efficiency, as it allows multiple transmitters to broadcast the same content simultaneously on the same frequency. Without accurate synchronization, signals from different transmitters could overlap destructively, leading to signal degradation, increased error rates, and poor reception quality. Therefore, maintaining stringent synchronization across the SFN is essential for increasing network throughput by decreasing length of guard intervals that account for timing discrepancies between transmitters.

Traditionally, SFNs have relied heavily on synchronization via GNSS, including GPS and GLONASS. This method, while widely adopted for its operational simplicity and precision, introduces a single point of failure due to its susceptibility to various vulnerabilities and underscores a critical need for more resilient and secure synchronization methods.

The Integrated Time Transfer synchronization, aimed at removing GNSS dependency within SFN networks, leverages the Time Transfer feature of the Nimbra transport platform. This technology facilitates precise time signal dissemination across the network, capitalizing on its inherent architecture to maintain synchronization [11]. Integrated Time Transfer system operates by embedding time signals within the data stream transmitted across the network. It requires a coherent network infrastructure, where each node is capable of extracting and utilizing these embedded time signals to synchronize its operations. Despite its innovative approach, this method encounters challenges in universal application across all DVB-T systems. Factors such as network configuration diversity, signal propagation delays, and the variable quality of network links can significantly impact its effectiveness. Specifically, environments with high network latency or those that lack uniformity in infrastructure design may not achieve the desired synchronization precision. While offering a level of resilience against common GNSS vulnerabilities such as signal jamming and spoofing, the Integrated Time Transfer synchronization's dependency on network infrastructure integrity introduces its own set of potential weaknesses. These include susceptibility to network-based disruptions and the need for robust, uniformly high-quality network connections to ensure consistent synchronization performance across the SFN.

The transition towards alternative synchronization methods for SFNs is fraught with technical, logistical, and infrastructural challenges. The establishment of a terrestrial time signal network, for instance, requires significant investment and strategic planning to ensure coverage, precision, and reliability that can match or surpass GNSS-based methods. Furthermore, the integration of multiple synchronization sources introduces new complexities in synchronization algorithms and system design, necessitating further research and development efforts.

C. eLoran

eLoran, an advanced evolution of the original Long Range Navigation (Loran) system, stands out as a robust terrestrial-based navigational and timing solution, designed to complement and, in certain scenarios, replace GNSS systems like GPS. Its operational premise relies on a network of high-powered, low-frequency time signal radio transmitters usable for trilateration that provide wide-area coverage, capable of penetrating environments where GNSS signals may be weak or obstructed. This characteristic, coupled with eLoran's resistance to common forms of interference and spoofing attacks, underlines its utility in critical navigational infrastructure.

The strength of eLoran lies in its signal's low frequency, which allows for reliable reception even in challenging conditions, making it an ideal candidate for secure, resilient time and frequency dissemination. This system's architecture is designed to offer an alternative or supplementary timing solution that mitigates the vulnerabilities inherent in satellite-based systems, particularly in scenarios where GNSS signals are compromised due to natural phenomena or deliberate interference.

Further development and deployment of eLoran systems across the globe, including significant investments by countries in establishing and maintaining eLoran infrastructure, reflect a strategic approach to safeguarding critical communication, navigation, and timing services against the increasing threats to GNSS reliability. The integration of eLoran into existing technological frameworks promises enhanced operational continuity and security, making it a cornerstone in the pursuit of GNSS-independent, resilient global positioning networks.

D. Time signal range limitations

The investigation into the maximum achievable range for the reception of time signals from longwave radio stations constitutes a critical research domain. The advent of advanced Digital Signal Processing (DSP) technologies offers promising avenues to extend the reception range, potentially facilitating national coverage. In the context of Russia, the operation of 11 longwave precise time signal stations hints at the possibility of achieving nationwide coverage, as suggested by references such as the ITU-R 1997 standard [6]. However, the vast expanse of Russia's territory necessitates empirical validation to confirm these theoretical capabilities.

Similar time signal radio station in Germany (DCF-77) is reported to have a reception range extending up to 2000 km. Despite this claim, there is a notable absence of comprehensive scientific investigations of this number. This gap in research underscores the imperative need for dedicated experimental studies aimed at accurately determining the maximum reception range of time signals.

III. Methods

The research begins with an exhaustive literature review to understand the current landscape of time synchronization, particularly emphasizing the DVB-T and DVB-T2 standards, Precision Time Protocol (PTP), and GNSS. This review serves to identify the state of the art and gaps in existing research.

Exploring the propagation of low-frequency radio signals forms a significant portion of our study. This involves investigating how these signals are received and developing antennas with diverse characteristics aimed at ensuring robust reception of time signals. Such an investigation is critical for devising a reliable system that operates effectively under various conditions.

In parallel, we focus on the creation of novel Digital Signal Processing (DSP) algorithms. These algorithms are designed to extract time signals from the noisy data received by the antennas, a key component in achieving accurate signal interpretation even in challenging environments.

At the heart of our experimental setup is a hardware platform developed around the STM32 microcontroller. Selected for its performance and availability, this platform is intended to function as a timing source for synchronizing SFN base stations.

To augment accuracy, especially during instances of signal loss, the system incorporates oven-compensated voltage-controlled oscillators (OCVCXO). Renowned for their stable signal performance over time, these devices are instrumental in maintaining synchronization precision.

The performance of this comprehensive setup is rigorously evaluated through physical tests under a variety of natural conditions and at different distances from the radio time signal source. Such evaluations are essential for validating the system's effectiveness in real-world scenarios.

Finally, the research develops algorithms capable of identifying discrepancies in both GNSS and ground-based time signals. These algorithms facilitate an internal switching mechanism between signal sources to ensure continuous synchronization of SFN base stations.

This methodological framework underscores our dedication to advancing SFN synchronization technology. By addressing each component of the synchronization process, from signal reception and processing to hardware innovation, we aim to establish a robust foundation for future developments in digital broadcasting networks.

IV. Anticipated Results

The anticipated outcomes of this study focus on the creation of an experimental device or a novel synchronization method tailored for SFNs. This initiative aims to leverage longwave precise time signal stations alongside supplementary sources to bolster resilience against GNSS interference. The endeavor involves engineering a device or methodology that is proficient in receiving a standard 1 PPS (pulse per second) time signal and a 10 MHz reference signal, both exhibiting minimal deviation from the national time scale.

Field evaluations will be conducted to ascertain the maximum feasible distance from the precise time signal radio stations' ground reference source while still maintaining the requisite accuracy and stability. Additionally, the project is set to devise a method for the rigorous assessment of the time signal's accuracy and stability, facilitating its evaluation under laboratory conditions complemented by the formulation of the necessary mathematical models and algorithmic support.

A pivotal feature of the developed device will be its capability to seamlessly transition between GNSS and terrestrial time signals, thereby ensuring a stable synchronization signal, which is crucial for adherence to DVB-T2 standards. The project aspires to achieve a precision goal of at least 10^{-10} Hz relative to the Coordinated Universal Time (UTC) scale, aligning with the stringent demands set forth for DVB-T2 broadcasting standards [11].

V. Conclusion

This research explores the integration of GNSS and longwave radio stations for enhancing time synchronization in SFN networks, addressing the vulnerabilities of GNSS systems. Through a multifaceted approach including literature review, analysis of GNSS vulnerabilities, exploration of alternative synchronization methods, and development of experimental devices, the study proposes a hybrid model for SFN synchronization. This approach not only aims to mitigate the risks associated with GNSS dependencies but also explores the potential of ground-based time signals for improving resilience and accuracy. The anticipated outcomes suggest promising directions for future research and practical applications in digital broadcasting networks, emphasizing the importance of diversifying time signal sources to ensure reliable and precise synchronization across SFN networks.

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