

BEYOND CONVENTIONAL RTCs: CHALLENGES, PROBLEM SOLVING APPROACHES AND EMERGING TECHNOLOGIES FOR MODERN TIMEKEEPING

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Abstract: Nowadays Real-Time Clocks (RTCs) are widely used in IoT, automotive, wearable and SoC systems to maintain accurate time. However, modern applications require RTCs to provide better accuracy, very low power consumption, secure timekeeping and synchronization between multiple devices. This review discusses four major challenges: frequency drift and accuracy, security, synchronization and ultra-low-power operation. Recent approaches such as temperature compensation, adaptive calibration, secure time synchronization, RBS, TPSN, resistor-less relaxation oscillators and conduction-angle-adaptive crystal oscillators are reviewed. The paper also discusses their limitations and future research directions toward accurate, secure, reliable and energy-efficient RTC systems.

IndexTerms – RTC, SoC, Internet of Things (IoT), Frequency Drift, MEMS Oscillator, clock skew, crystal oscillator, multi-hop synchronization, temperature-compensated bias current generator, PTAT voltage source, relaxation oscillator, shunt regulator, conduction-angle-adaptive crystal oscillator (CAAXO), automotive electronics, wearable devices, GESD (Generalized extreme studentized deviate), RBS (Reference Broadcast Synchronization), TPSN (Timing-Sync Protocol for Sensor Networks).

I. INTRODUCTION

As we know Real-Time Clock (RTC) technology has matured significantly and has traditionally focused on maintaining time using a low-frequency oscillator and a backup power source. However, the rapid growth of modern applications such as the Internet of Things (IoT), automotive electronics, wearable devices, edge computing and safety-critical system-on-chip (SoC) platforms has introduced requirements which are beyond the capabilities of conventional RTC architectures. Also, these applications require ultra-low-power operation, high timing accuracy, enhanced security, fault tolerance, system synchronization and long-term reliability. Here, traditional RTCs face challenges related to temperature-induced frequency variation [1], long-term oscillator drift [1], continuous power consumption, dependence on backup energy sources, unauthorized time manipulation, clock failures and limited synchronization capabilities. Therefore, innovative approaches are required to overcome these limitations while maintaining the low-power and compact characteristics essential for modern embedded systems.

This paper reviews the major challenges faced by modern RTC systems and analyses existing approaches for addressing these challenges. Also, it further discusses recent technological advancements in the areas of accuracy, ultra-low-power operation, secure and authenticated timekeeping and system synchronization. Finally, the paper identifies open research challenges and future opportunities for the development of accurate, energy-efficient, secure and reliable RTC architectures. Modern RTC solutions combine precision, power efficiency and security, making them indispensable for today's connected and time-critical applications.

II. Evolution of RTC Technology:

S.No.	Generation of RTC	Main Technology	Main Limitation
1	Conventional	Crystal Oscillator [1]	Frequency Drift [1]
2	Low-Power	Reduced Power design [8]	Accuracy reduced [8]
3	Crystal Oscillator-based	Temperature Compensation [9]	Expensive [9]
4	MEMS	MEMS Oscillator [4]	Integration complexity [4]
5	Network synchronized	External time synchronization [5]	Communication/Power overhead [5]

III. Major Challenges in Modern RTC Technology:

A. RTC Security:

Time synchronization is critical in modern distributed systems where number of devices need to maintain a common time for communication, scheduling, event ordering and coordinated operation [4]. Also, traditional synchronization methods mainly focus on accuracy and assume that the devices and timing messages are trustworthy. However, an attacker may modify, replay [4], delay or stops synchronization messages or compromise a device and shows us incorrect time [3]. Here, a delay attack [4] is particularly difficult to detect because the attacker can delay a valid message without changing its contents [3]. Therefore, authentication alone may not be sufficient to ensure correct time synchronization.

For RTC-based systems, incorrect time can affect event logging, authentication, certificate validation, access control and replay protection. Hence, modern RTCs need to provide not only accurate timekeeping but also secure and trustworthy time updates. There are some key challenges like unauthorized modification of time [3], replay and delay attacks [3], compromised devices providing incorrect time [4] and maintaining security with low power and communication overhead.

B. Synchronization of RTC based distributed systems:

As we know in a system where multiple devices work together, each device has its own local clock. Although all the clocks start at the same time, they gradually become different because of variations in oscillator frequency, temperature, aging and other factors [5]. So, this creates clock offset and clock skew, which becomes difficult for different devices to maintain a common time [5]. Here, synchronization becomes especially challenging in low-power systems because communication, computation and synchronization activities consume additional energy. Also, wireless systems face limited bandwidth, communication delays, changing network conditions and scalability issues when the number of devices increases [5]. The literature therefore identifies accuracy, complexity, convergence time, scalability, energy efficiency and fault tolerance as important factors when designing a synchronization method [5].

C. Ultra-Low-Power Operation:

RTCs need to operate continuously, even when the main parts of an SoC or electronic device are in low-power or sleep mode. Therefore, reducing RTC power consumption is important for battery-powered IoT devices, wearables and low-power embedded systems [8]. Conventional crystal oscillators provide good frequency stability, but reducing their power consumption can make start-up and reliable oscillation more difficult [8]. On the other hand, fully integrated relaxation oscillators can reduce area and eliminate external components but their frequency can be more sensitive to temperature, supply voltage and process variations [6]. For example, the 2018 work achieved 271 nW power consumption but reported temperature and voltage dependencies of 138 ppm/°C and 13.9 ppm/mV, respectively [6].

Therefore, the main challenge is to achieve very low power consumption while maintaining sufficient frequency accuracy, stable operation, reliable start-up and robustness across temperature and supply variations [6][7].

D. Frequency Drift and Accuracy:

The frequency accuracy of an RTC is influenced by temperature variation and the frequency characteristics of the crystal oscillator, which results in frequency drift during operation [9]. Here, temperature-compensated crystal oscillators were developed to reduce the effect of temperature on oscillation frequency using direct and indirect compensation techniques [9]. Also, even small frequency deviations lead to significant time errors during long-term RTC operation [9]. Therefore, maintaining stable frequency and accurate time over a wide temperature range remains an important challenge for RTC systems.

IV. Proposed Problem-Solving Framework and Future Scope:

A. RTC Security:

In this literature review Ganeriwal et al. proposed a secure time-synchronization approach that adds authentication to pairwise, group and multi-hop synchronization [4]. This helps prevent unauthorized devices from modifying or injecting timing information while considering the additional energy and communication overhead [4]. However, authentication alone cannot prevent delay attacks because a valid message can still be delayed by an attacker. To resolve this problem, Song et al. proposed detecting abnormal timing information using GESD-based outlier detection and threshold-based filtering [3]. These methods help identify and reject suspicious synchronization values.

As a part of future scope of RTC security; For modern RTC systems, these approaches can be extended by combining hardware-protected RTC registers, secure access control, authenticated time updates, tamper detection and a trusted backup time source [4]. This can provide secure timekeeping while maintaining the low-power requirements of always-on RTC systems [4].

B. Synchronization of RTC based distributed systems:

As part of advancements, different synchronization protocols have been developed to estimate the difference between local clocks, correct the clock offset and skew. From this literature review, Reference Broadcast Synchronization (RBS) allows receiving devices to compare the time at which they receive a common reference message [5], while Timing-Sync Protocol for Sensor Networks (TPSN) uses synchronization between nodes to establish a common time reference [5]. The Rhee et al. paper also discusses methods for estimating clock offset and clock skew and evaluating their synchronization performance [5]. Here, for modern RTC-based systems, these techniques can be extended by allowing the RTC to operate independently for most of the time and performing synchronization periodically. Also, the system can measure the time difference and clock drift and apply a correction to the local RTC and then continue autonomous operation until the next synchronization event. So, this reduces unnecessary communication and power consumption while maintaining acceptable timing accuracy.

Future synchronization techniques can focus on improving the balance between synchronization accuracy, energy consumption, communication overhead and scalability. Also, adaptive synchronization mechanisms that consider clock drift and changing network conditions could further reduce synchronization overhead while maintaining the required timing accuracy [5].

C. Ultra-Low-Power Operation:

To reduce power and area, Asano et al. proposed a fully integrated resistor-less relaxation oscillator. Here, the design uses a temperature-compensated bias current generator, PTAT voltage source, relaxation oscillator, shunt regulator and output logic [6]. Here, by removing resistors reduces the circuit area, while the compensation circuits help reduce temperature-related frequency variation. The proposed design generates a 32.5-kHz clock with 271-nW simulated power consumption and an area of only 0.022 mm² [6].

A more recent approach by Wang et al. uses a conduction-angle-adaptive crystal oscillator (CAAXO). Instead of keeping the oscillator conduction fixed, the conduction angle is adjusted according to the oscillation amplitude. This allows the oscillator to start when there is no oscillation and then improve its energy efficiency as the oscillation amplitude increases. The fabricated 28-nm implementation operates from a 0.38-V supply and achieves 0.36 nW at 25°C, while operating from -20°C to 85°C [7].

The results of these studies indicate that future RTC research should focus on further improving the trade-off between power consumption, frequency stability, start-up capability and environmental robustness. So, combining adaptive oscillator control with calibration and temperature-compensation techniques may provide a promising direction for achieving ultra-low-power and accurate RTC operation.

D. Frequency Drift and Accuracy:

Temperature compensation can be implemented by sensing the operating temperature and applying a corresponding correction to reduce oscillator frequency deviation [10]. Here, recent approaches use digital and adaptive calibration to improve RTC frequency accuracy [10]. For example, Luo et al. proposed an adaptive binary-search-based RTC calibration technique in which an on-demand 16-MHz crystal oscillator is used as a frequency reference to calibrate an always-on 1-MHz on-chip RTC [10]. The proposed technique achieved a reported temperature coefficient of 0.63 ppm/°C from -40°C to 125°C [10]. Another recent direction uses time-domain techniques to improve the accuracy of temperature-compensated crystal oscillators.

These approaches indicate a transition from conventional fixed compensation toward adaptive and digitally assisted calibration, although the trade-off between accuracy, power, area and calibration complexity remains an important research challenge.

VII. Conclusion:

From this literature review we have concluded all four important challenges in modern RTCs: accuracy, security, synchronization and power consumption. The temperature compensation and adaptive calibration can improve frequency accuracy, while secure synchronization techniques can protect time information from attacks. Also, RBS and TPSN provide approaches for synchronizing distributed devices, but communication and energy overhead remain challenges. From modern ultra-low-power oscillator designs we can say that RTC power consumption can be significantly reduced while maintaining reliable operation. As a part of future scope of RTC research should focus on combining adaptive calibration, low-power oscillator design, secure time updates and energy-efficient synchronization to achieve accurate, secure, reliable and ultra-low-power timekeeping.

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