A Review of Crystal Oscillators Imperfection: Linking Frequency Deviations to Carrier Frequency Offset and Phase Noise

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This paper systematically investigates imperfections of crystal oscillators imperfection, which demonstrates frequency deviations and their relationship and impact on physical layer authentication. By analyzing the fundamental properties of the crystal oscillator, frequency deviations can be divided into frequency inaccuracy, which represents systematic offsets from the nominal frequency, and frequency instability, which denotes time-dependent fluctuations. We separately analyze both internal and external factors influencing these deviations and highlight their dual impact on oscillator performance and radio frequency fingerprinting (RFF) features, including carrier frequency offset (CFO) and phase noise (PHN). By analyzing internal factors such as material quality and crystal aging, we provide a new perspective that explores the relationship between CFO and PHN and oscillator deviations, providing new insights into their origination and potential for secure communication. By analyzing external influences like temperature and power supply noise, challenges in leveraging CFO and PHN for authentication under varying environmental conditions are discussed, along with future research directions aimed at enhancing robustness and reliability.

Index Terms—**Crystal Oscillator, Frequency Deviations, Carrier Frequency Offset (CFO), Phase Noise, Radio Frequency Fingerprinting (RFF).**

I. Introduction

The crystal oscillator is a fundamental component in virtually all wireless communication devices, playing a critical role in frequency control by ensuring accurate time-keeping and precise frequency generation [1]. Crystal oscillators rely on the piezoelectric effect of quartz crystals, where an applied voltage induces mechanical resonance, generating a stable and periodic electrical signal. Crystal oscillators are important across diverse applications, including wireless communication systems, precision navigation (e.g., GPS), and digital electronics, where synchronization and timing accuracy are paramount.

However, crystal oscillators are not free from imperfections. Despite their high stability, the frequency output of crystal oscillators is not perfectly accurate or consistent. Specifically, frequency in an oscillator is determined by defined origins, such as a defined resonance in the crystal, interrogating electronics, induced biases, and random perturbations. Although oscillator manufacturers strive to produce precise frequencies using the best production methods, manufacturing errors are inevitable. Therefore, each oscillator, though precise in its operation, cannot maintain an ideal nominal frequency and may differ slightly from others even of the same design [2].

The frequency generated by an oscillator is influenced by multiple factors, including internal and external factors affect their frequency instability and inaccuracy. Internal factors include crystal aging, material quality, and manufacturing defects, which introduce long-term deviations in frequency. External factors such as temperature variations, drive level fluctuations, power supply noise, and environmental influences like humidity and electromagnetic interference (EMI) further exacerbate instability. These imperfections can manifest as a part of carrier frequency offset (CFO) and phase noise (PHN), which significantly impact the performance of wireless systems.

The CFO, which refers to the systematic deviation of the oscillator's frequency from its nominal value, results in misalignment between the transmitter and receiver frequencies. This misalignment will cause inter-carrier interference (ICI) in systems employing orthogonal frequency-division multiplexing (OFDM) and reduce demodulation accuracy. On the other hand, PHN represents random phase fluctuations that result in spectral spreading around the carrier frequency, reducing the signal-to-noise ratio (SNR), especially in high-order modulation schemes, where the margin for error is minimal. These phenomena collectively degrade overall system performance, affecting data throughput, reliability, and efficiency. Interestingly, these imperfections do not solely introduce challenges, they also offer unique opportunities. The distinct frequency deviations and phase noise characteristics of individual oscillators create unique hardware-specific signatures known as radio frequency fingerprinting (RFF). These signatures can be exploited for physical layer authentication, such as device identification and spoofing detection, providing a new perspective on utilizing oscillator imperfections for enhanced security. [3]–[6].

In recent years, several contributions have been proposed to review the characterization of frequency deviations and oscillator impairments-based physical layer authentication. Studies in [2], [7], [8] presented comprehensive reviews of the characterization of frequency deviations, including frequency inaccuracy and frequency instability of oscillators. Walls *et al.* [9], [10] reviewed environmental and other fundamental limits on the frequency deviations of crystal oscillators. In addition, studies in [11], [12] summarized the model, properties, and applications of PHN. Huan *et al.* [13] also reviewed the characteristics of CFO and its application on RFF identification. Although existing research has focused on the characterization and limitation of frequency deviations and physical layer

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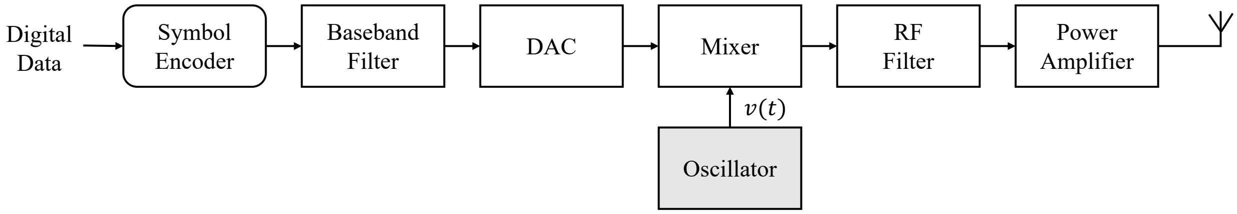

Fig. 1: Block diagram of a typical wireless transmitter.

authentication based on oscillator impairments separately, a critical gap remains in understanding the internal relationship between these two aspects. Most current studies consider oscillator frequency inaccuracy and instability as isolated performance metrics without delving into how these metrics affect the usability of oscillators for authentication purposes. This oversight limits the ability to fully exploit oscillator imperfections in real applications. To address this gap, this paper systematically investigates the frequency inaccuracy and instability characteristics of crystal oscillators, with a focus on exploring their internal relationship with CFO and PHN. By analyzing the fundamental properties of oscillators, this paper first characterizes oscillator deviations and categorizes deviations into frequency inaccuracy and frequency instability. Then, this paper examines internal and external factors influencing frequency inaccuracy and instability. Furthermore, we analyze the relationship between frequency deviations and CFO and PHN and explain the origination of the CFO and PHN. Finally, this paper highlights challenges in leveraging CFO and PHN-based techniques under varying environmental conditions and presents potential directions for future research to improve the robustness and reliability of physical layer authentication methods.

II. Characterization of Oscillator Deviations

A typical wireless transmitter structure is illustrated in Fig. 1. The transmitter hardware comprises five primary components: filter, digital-to-analog converter (DAC), oscillator, mixer, and power amplifier. Among these, the oscillator is used to generate a stable sine wave and collaborates with a mixer for up-conversion. The quartz crystal oscillator, which is a widely used type, consists of three main components: the resonator, the substaining circuit, and the oven [10]. The resonator is the core component that determines the output frequency of the oscillator. It leverages the piezoelectric effect of the quartz crystal to generate mechanical vibrations. When the frequency of an applied voltage matches the resonant frequency of the crystal, resonance occurs, resulting in a stable alternating voltage across the electrodes. The sustaining circuit, also known as the feedback network, ensures the stability and maintenance of oscillations. By incorporating amplifiers and phase compensators, the circuit compensates for energy loss in the resonator during continuous oscillations. The resonator will lose energy during the continuous oscillation process. Its main function is to feed back part of the output signal to the input to compensate for the gain and phase to maintain the continuity of the oscillation. The oven provides temperature stabilization, particularly for the resonator, as temperature fluctuations significantly affect performance. Together, these three components contribute to the frequency and phase deviations of the oscillator.

The instantaneous output voltage $V(t)$ at time t of an oscillator can be expressed as

$$V(t) = V_0 \sin \Phi(t), \tag{1}$$

where V_0 represents the nominal amplitude, and $\Phi(t)$ is the instantaneous phase of the oscillator which deviates from the nominal frequency v_0 [7], [12]. Since phase and frequency can be converted into each other, the corresponding instantaneous frequency $v(t)$ is given by

$$v(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt}. \tag{2}$$

And then define a dimensionless quantity $y(t)$ representing the normalized frequency deviation of $v(t)$ from its nominal value, which can be expressed as

$$y(t) = \frac{v(t) - v_0}{v_0} = \frac{\Delta v}{v_0}. \tag{3}$$

Integrating $y(t)$ yields the phase deviation $x(t)$, which can be written as

$$x(t) = \int_0^t y(\tau) d\tau. \tag{4}$$

Lindsey *et al.* [14] proposed a framework to characterize oscillator frequency and phase deviations in terms of the Nth-order structure function. The oscillator phase process $\Phi(t)$ in (1) can be expressed as

$$\Phi(t) = \omega_0 t + \underbrace{\sum_{k=2}^{N} \frac{\Omega_{k-1}}{k!} t^k}_{\text{long-term phase drift}} + \underbrace{[\psi(t) - \psi(0)]}_{\text{short-term phase instability}} + \Phi(0), \tag{5}$$

where $N \geq 2$, ω_0 is the constant mean radian frequency, Ω_k represents a set of time-independent random variables modelling kth-order frequency drifts, and $\psi(t)$ represents a random process to characterize the short-term instability. When $N = 2$, that is, an oscillator with a linear frequency drift, the phase deviation in (4) simplifies to

$$x(t) = x_0 + y_0 t + \frac{1}{2} D t^2 + \phi(t). \tag{6}$$

Oscillator deviations can be categorized into two types. The first category, frequency inaccuracy, includes systematic deviations such as frequency drift (D), frequency offset (y_0), and time offset (x_0), which collectively represent deviations from the nominal frequency. The second category, random deviations $\phi(t)$, quantifies the short-term frequency constancy of the oscillator [8]. The frequency inaccuracy of a oscillator refers to an systematic offset from the specified or ideal frequency. It is a measure of how far the actual frequency output is from the intended target frequency. The frequency instability is the variation in frequency over a period time due to dynamic factors. It captures fluctuations in the frequency output caused by environmental conditions, noise, and internal device behaviors.

III. Factors Influencing Frequency Accuracy

This section delves into the intricate factors influencing the frequency inaccuracy of oscillators, categorized into internal and external factors. The internal factors can be further categorized into crystal aging, crystal material and cutting methods, and manufacturing process errors. The external factors encompass temperature variations, drive level discrepancies, and tuning port reference voltage drift.

A. Internal Factors

1) Crystal Aging

Crystal aging refers to the gradual change in the frequency of a crystal oscillator over time due to physical and chemical changes within the crystal structure [15]. Over time, phenomena such as internal stress relaxation, surface contamination, circuit aging, and quartz outgassing contribute to slow drift in the crystal's natural resonant frequency [10], [16]. These changes alter the property of the oscillator and lead to long-term deviations from the nominal frequency. Filler *et al.* [16] observed a logarithmic trend in aging effects: higher frequency shifts occur during the initial operational phase due to rapid stress relaxation and impurity diffusion. Subsequently, the frequency drift rate diminishes, stabilizing the oscillator's performance. This stabilization renders long-term aging effects more predictable. Crystal aging is thus a critical determinant of oscillator frequency inaccuracy [17].

2) Crystal Material and Cutting Methods

The frequency instability of a crystal resonator is also influenced by its material properties and cutting methods. Quartz is the most widely used material due to its piezoelectric properties, which enable stable frequency generation. However, the specific type of quartz and its purity significantly impact performance. High-purity quartz reduces internal imperfections, minimizing energy losses and frequency deviations. Additionally, lattice imperfections and changes in the crystal structure further contribute to long-term frequency instability. In addition, the shape of the crystal, including the shape of the wafer and the surface quality of the wafer, also has an important influence on the performance and working stability of the crystal oscillator. Cutting techniques such as AT-cut, BT-cut, and SC-cut result in distinct frequency-temperature characteristics, and they exhibit different frequency transient behaviors [18]. For instance, For instance, AT-cut and BT-cut resonators exhibit initial thermal shocks causing frequency deviations of -36.7 ppm and $+27.6$ ppm, respectively. Over 2.5 thermal time constants, these deviations stabilize below 10^{-3} ppm. Conversely, TS-cut resonators display persistent deviations exceeding 4×10^{-3} ppm. Therefore, the design of the resonator, material purity, isotopic purity, crystal integrity, processing, and variations of new piezoelectric materials are critical. Even tiny defects or stresses introduced during these processes can lead to different frequency inaccuracies.

3) Manufacturing Process Errors

Manufacturing process errors play a critical role in determining the frequency inaccuracy of oscillators. Small deviations during the crystal cutting, assembly, and welding can induce mechanical stresses, which alter the nonlinear elastic behavior of the crystal and lead to frequency shifts [9]. For example, improper assembly alignment or uneven pressure can create residual stresses, leading to deviations from the intended frequency. The relationship between stress and crystal frequency variation is shown as [19]

$$\Delta v = K_f \frac{v_0^2}{D} F, \tag{7}$$

where D is the diameter of the crystal, K_f is the stress sensitive coefficient, and F is the stress value.

Furthermore, defects introduced during soldering or gluing components can also affect the frequency inaccuracy of the oscillator. These errors are increased by the tolerances of the electronic components used in the oscillator circuit, such as capacitors and inductors, which may not exactly match the design specifications. The relationship between small changes in the capacitance and inductance of an oscillator circuit and the frequency deviations is given by [10]

$$\frac{\Delta v}{v_0} \approx \left(\frac{1}{1+\frac{2f_f}{BW}}\right)\left(\frac{Q_c}{Q}\right)\left(\frac{dC_c}{C_c}+\frac{dL_c}{L_c}\right), \tag{8}$$

where BW is the filter bandwidth, f_f represents the frequency offset of the center frequency of the filter from the carrier frequency, Q and Q_c are the Q-factor of the oscillator and tuned circuit, and C_c and L_c are the capacitance and inductance of the circuit, respectively. Therefore, even small manufacturing inconsistencies can result in varying frequency inaccuracy.

B. External Factors

1) Temperature

Temperature is the other most important factor affecting the frequency inaccuracy of an oscillator besides aging. As stated in Section III-A2, the sensitivity of resonator frequency to temperature fluctuations is profoundly influenced by the crystal-cutting method. For instance, AT-cut crystals, specifically designed to minimize temperature sensitivity, can restrict relative frequency variations to within $\pm 2 \times 10^{-5}$. In addition, a key phenomenon related to temperature effects is thermal hysteresis. This phenomenon refers to the irreproducibility of frequency-temperature characteristics when the resonator undergoes cyclic temperature variations, leading to observable frequency discrepancies between successive temperature cycles. Kutsters *et al.* [20] conducted a detailed experimental study on quartz resonators manufactured with different cutting techniques and material compositions. Their analysis revealed that thermal hysteresis arises from lattice defects, which compromise the resonator's structural homogeneity and contribute to such frequency inaccuracies.

2) Drive Level

The drive level or the crystal electric also affects the oscillator frequency. The quantitative relationship between drive level and frequency deviation can be expressed as [8]

$$\frac{\Delta v}{v_0} \approx ki^2, \tag{9}$$

where i is the alternating current passing through the crystal, k is a constant determined by the crystal's intrinsic properties. The frequency changes as the square of the drive current, and the degree of change depends on the crystal cutting method and the blank curvature [21]. Crystals with distinct cutting orientations exhibit varying sensitivities to drive levels, necessitating precise calibration to achieve optimal performance. Long-term frequency instability and aging characteristics will deteriorate with a large driving electric current. Conversely, insufficient drive levels lead to a dominance of noise currents over the crystal's electric current, thereby compromising short-term frequency instability and increasing phase noise.

3) Tuning Port Reference Voltage Drift

The tuning port reference voltage drift directly affects oscillator frequency inaccuracy by influencing tuning sensitivity and range. Even minor voltage instability, such as jitter or drift, can lead to significant frequency deviations, especially in oscillators with high tuning sensitivity. This factor affects different types of oscillators differently and is related to the tuning voltage sensitivity of the oscillator.

IV. Factors Influencing Frequency Instability

Frequency instability in oscillators arises from a combination of intrinsic and extrinsic factors. Internally, noise mechanisms such as Johnson noise, shot noise, flicker noise, and phonon scattering degrade oscillator performance by introducing random fluctuations in phase and frequency. Externally, environmental influences, including power supply noise, acceleration, and other environmental factors like temperature, humidity, electromagnetic interference, and radiation, exacerbate instability, often in nonlinear and coupled ways. These factors are explored in detail below.

A. Internal Factors

1) Johnson Noise

Thermal noise, also known as Johnson noise, arises from passive components within the oscillator, such as resistance, due to the thermal or Brownian motion of electrons. It is an inherent and unavoidable noise source characterized by its uniform power spectral density across all frequencies, resulting in white noise behavior. In the context of oscillators, Johnson noise contributes significantly to phase noise and frequency stability degradation. The Johnson noise in an oscillator can be expressed as [22]

$$\mathcal{L}(f) = \frac{kT}{2Q_L P f^2}, \tag{10}$$

and

$$\sigma_y(\tau) = \frac{1}{Q_L}\sqrt{\frac{kT}{2P\tau}}, \tag{11}$$

where $\mathcal{L}(f)$ represents the single-sideband phase noise at offset frequency f, $\sigma_y(\tau)$ is the representation of noise in the time domain, k is Boltzmann's constant, T is the temperature in K, Q_L is the loaded Q-factor of the resonator, and P is the total power delivered to the resonator and the load.

2) Shot Noise

Shot noise is a type of noise generated by the discreteness of electrons or photons. In oscillators, shot noise is usually caused by current fluctuations in active components such as transistors or diodes. The power spectral density (PSD) of shot noise, a key parameter in characterizing its impact, is expressed as [12]

$$S_{shot}(f) = 2qI_D, \tag{12}$$

where q is the electron charge and I_D is the current through a junction. Shot noise is inherently frequency-independent, exhibiting a white noise spectrum. However, its magnitude depends directly on the biasing conditions of the active device, such as the junction current I_D.

3) Flicker Noise

Flicker noise in oscillators originates from random charge capture and release processes in surface states and other traps [23]. Specifically, flicker noise is caused by the random capture and release of charge in surface states and traps in devices such as transistors. The PSD of flicker noise is denoted as

$$S_{flicker} = \frac{k_f}{f}, \tag{13}$$

where k_f is a flicker noise coefficient of the particular device. As stated in [10], flicker phase modulation (PM) noise in the holding circuit will cause flicker frequency modulation (FM) noise also to affect the oscillator output frequency, and its single-sideband phase noise is

$$\mathcal{L}(f) = \mathcal{L}_{ckt}(1\,\mathrm{Hz})\frac{v^3}{4f^3 Q_L}, \tag{14}$$

and

$$\sigma_y(\tau) = \frac{1}{Q_L}\sqrt{\ln 2\mathcal{L}_{ckt}(1\,\mathrm{Hz})}, \tag{15}$$

where $(1\,\mathrm{Hz})$ is the flicker PM noise at $f = 1$ Hz and τ is any measurement time in the flicker floor range.

4) Phonon Scattering in the Resonator

Phonons are acoustic vibration quanta in crystalline materials. Phonon scattering refers to the phenomenon that phonons are scattered due to interactions with other phonons, electrons, impurities or grain boundaries. These scattering mechanisms lead to energy dissipation and phase perturbations, which reduce the Q-factor of the oscillator. And [10] pointed out that phonon scattering in the resonator will increase the FM noise in the resonator, thereby affecting the frequency instability.

B. External Factors

1) Power Supply Noise

Power supply voltage fluctuations affect the driver output voltage, switching edge slope, and time interval error, ultimately causing frequency jitter. The extent and characteristics of this jitter depend on the amplitude and frequency of the power supply voltage fluctuations, as well as the power supply rejection ratio (PSRR) and time averaging effect of the driver [24]. In voltage-controlled oscillators (VCOs), which rely heavily on loop dynamics, power supply noise becomes one of the main sources of phase noise.

2) Acceleration-Induced Noise

Oscillator crystals are highly sensitive to acceleration forces, such as vibrations, centrifugal effects, and mechanical impacts, which degrade phase noise and increase frequency jitter [25]. When subjected to acceleration, the resonator experiences deformation that influences its elastic constants and vibrational modes, resulting in frequency shifts. This acceleration-induced noise is one of the sources of short-term frequency instability and is mainly determined by the speed of the sound wave and the size of the constraining structure. When there is an external acceleration, the resonator will deform, and this deformation can affect the frequency in two ways: one is to disturb the speed of the sound wave, and the other is to change the size of the constraining structure. Specifically, the acceleration will cause the stress distribution inside the resonator, which will change its elastic constant and ultimately affect the resonant frequency of the resonator. [26]. The acceleration-induced frequency shift can be written as

$$\frac{\Delta v}{v_0} = \int_V cg^2 dV, \tag{16}$$

where c is the shift in the effective elastic constants brought on by the acceleration-induced biasing deformation field, g represents the normalized mechanical displacement vector's gradient related to the vibration mode, and V denotes the undeformed volume of the resonator.

3) Environmental Factors

Environmental factors, including temperature fluctuations, humidity variations, electromagnetic interference (EMI), and ionizing radiation, also play a vital role in influencing the frequency instability of oscillators. Among these factors, temperature fluctuations are particularly critical. Temperature changes reduce the Q value of the crystal, thereby increasing phase noise, especially in the mid- and high-frequency ranges. Humidity variations can also alter oscillator performance by affecting the dielectric properties of materials within the circuit, leading to subtle frequency deviations. Additionally, prolonged exposure to high humidity may induce corrosion or contamination on the crystal surface, further degrading its performance. Allan *et al.* [27] experimentally demonstrated that temperature and humidity have significant nonlinear and interdependent effects on the frequency output of the oscillator. And different types of oscillators (such as quartz, rubidium, cesium, and hydrogen) have varying sensitivities to these environmental parameters. For quartz crystal oscillators, the active sag phenomenon can cause significant changes in frequency coefficients and even changes in sign.

EMI can affect the frequency instability of the system by causing timing jitter and phase noise in the oscillator circuit through mechanisms such as induced noise voltage, external noise sources, and impedance mismatch [28]. EMI can significantly degrade frequency in in sensitive environments, particularly when oscillators are exposed to high-intensity electromagnetic fields. The ionizing radiation, including gamma rays, high-energy electrons, protons, and heavy ions, impacts oscillator frequency by altering the material properties of the resonator substrate. For example, when ionizing radiation interacts with a material, it causes changes in the density, thermal conductivity, or internal stress inside the material. In a high-energy radiation environment, charges may accumulate on the surface and inside the material, forming traps. These traps affect the electrical properties of the material, which in turn affects the frequency of the resonator. Different types of radiation affect the resonator performance differently, and the frequency deviation is roughly proportional to the square root of the total radiation dose [29].

V. ORIGINATION OF CFO AND PHN

The overall frequency deviation in an crystal oscillator has been defined in [9], [10], which can be written as

$$\begin{cases} \dfrac{\Delta v}{v_0} = \dfrac{1}{2Q}\left(1+\left(\dfrac{2fQ}{v_0}\right)^2\right)^{-1/2} d\phi(f), \\ \dfrac{\Delta v}{v} \approx \dfrac{\Delta v}{v_{res}} + \dfrac{1}{2Q}\left(1+\left(\dfrac{2fQ}{v_0}\right)^2\right)^{-1/2} d\phi(f) \end{cases} \tag{17}$$

where f is the frequency offset away from the carrier frequency v_0, v is the output carrier frequency, $d\phi(t)$ is a small change in loop phase at offset frequency f, v_{res} is the output frequency of the resonator, and Q represents loaded quality factor (Q-factor) of the resonator. The Q-factor is a dimensionless value used to describe the quality of vibration in a vibration system (such as mechanical vibration and electromagnetic vibration). It is used to measure the energy loss of the system at its resonant frequency. In an oscillator system, it is defined as the ratio of the energy stored in the oscillator to the energy lost in each oscillation cycle. The Q-factor of the oscillator is mainly affected by the internal and external factors as stated in Section III and Section IV.

In the realm of physical layer authentication, the radio frequency fingerprinting (RFF) features originate from the inherent impairments embedded in the hardware components, which is unique to a wireless device [21]. Due to internal factors such as material and processing errors during the oscillator manufacturing process, different oscillators produce different carrier frequency offset (CFO) and PHN features, which can be used to uniquely identify the transmitter [13], [30]. Figure 2 reveals the origin of CFO and PHN and their intrinsic connection with oscillator deviations.

In physical layer authentication, CFO is defined as the frequency deviation of the received signal relative to the expected frequency due to the incomplete matching of the carrier frequencies at the transmitter and receiver. There are three modules that may introduce CFO: transmitter oscillator, receiver oscillator, and Doppler effect. Since the oscillator at the transmitter and at the receiver are independent, the frequency offset caused by the transmitter and the oscillator are independent of each other. Furthermore, when the transmitter or receiver moves relative to each other, the frequency of

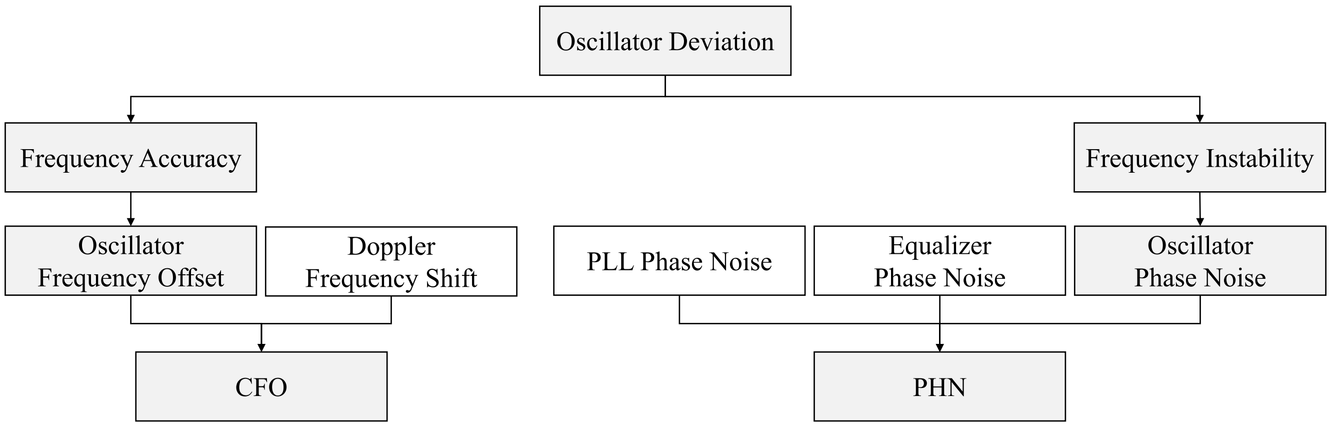

Fig. 2: The framework of origination of CFO and PHN.

the signal changes due to the Doppler effect. This effect is particularly significant in high-speed moving communication environments, such as satellite communications or mobile communications in high-speed vehicles. It is noticed that although there is the existence of a Doppler frequency shift, the CFO component caused by the oscillator plays a dominant role in the whole CFO model [30]. As shown in Fig. 2, the long-term oscillator deviation, that is, frequency inaccuracy, is the primary cause of the CFO.

PHN refers to the random fluctuations in the phase of the system output signal caused by various noises. It is introduced by three modules: oscillator, phase-locked loop (PLL), and channel equalizer. The oscillator is one of the primary sources of phase noise in communication systems. This noise originates from the inherent thermal noise, flicker noise, and power supply noise within the oscillator circuit. The PLL introduces phase noise due to imperfections in its components, including the reference oscillator, charge pump, loop filter, and VCO. The channel equalizer contributes to phase noise primarily through its phase estimation error when conducting channel estimation. As shown in Fig. 2, the short-term oscillator deviation, that is, frequency instability, contributes to the oscillator phase noise.

VI. Challenges and Future Directions

Although there are a lot of studies using CFO and PHN for authentication, they are not only affected by unique internal hardware characteristics but also by external factors such as temperature, as discussed in Sections III and Section IV. Zhang *et al.* [31] measured frequency deviations of different devices at different times and showed that frequency deviations are not stable in both the short and long term. Another observation in [13] is that different devices have similar variations on the same day. The above phenomenon shows that although CFO and PHN are affected by external factors, they have similar influences on the changing trends of crystal oscillators of different devices. Therefore, more effective authentication methods using CFO and PHN need to be studied in the future. To address this challenge, we discuss three promising research directions in this section.

A. Development of Robust Mathematical Models

A critical future direction involves constructing robust mathematical models incorporating external environmental factors such as temperature, humidity, and power supply fluctuations. These models enable accurate prediction and compensation of CFO and PHN variations. Advanced techniques like multi-modal data fusion could combine these external parameters with RF signal characteristics to develop holistic models. Real-time monitoring systems leveraging IoT sensors could provide continuous environmental data acquisition, enabling dynamic and adaptive adjustment of authentication frameworks. Future work could also explore the scalability of these models across varying environmental conditions and device types, ensuring generalizability and broad applicability in real-world scenarios.

B. Advanced Time Series Analysis for CFO and PHN

Time series modeling is pivotal in understanding the temporal dynamics of CFO and PHN variations. Leveraging modern machine learning approaches such as LSTM (Long Short-Term Memory) networks can uncover hidden temporal patterns and predict future trends. By identifying trends under controlled environmental conditions, predictive models can improve the robustness and reliability of device authentication frameworks. Chen *et al.* [32] have studied the time-domain shift problem of RFF using unsupervised contrastive learning, which significantly improves the robustness of physical layer authentication. Thus, advanced time series analysis for RFF is a promising future direction for physical layer authentication.

C. Separating Intrinsic Hardware Characteristics from External Variations

Distinguishing intrinsic hardware characteristics from externally induced variations is crucial for stable feature extraction. Advanced signal processing techniques, such as wavelet transforms, empirical mode decomposition (EMD), and singular spectrum analysis (SSA), could isolate intrinsic signals from noise or external trends. Future research could also explore machine learning-based denoising methods, such as convolutional denoising autoencoders, to enhance the separation process. Additionally, incorporating domain knowledge into feature selection and extraction algorithms could help identify and emphasize hardware-specific attributes, making the authentication process more accurate and less prone to environmental interference.

VII. Conclusion

This paper provides a comprehensive analysis of the imperfections of crystal oscillators and their relationship with CFO and PHN, emphasizing their dual role as both performance challenges and identification opportunities in physical layer authentication. Internal factors, such as material quality and crystal aging, combined with external influences, like temperature and power supply noise, contribute to frequency deviations that degrade system performance. However, these deviations also generate unique RFF features that can serve as reliable authentication markers. To overcome the instability caused by external conditions, the study recommends future research directions, including developing environmental compensation models, applying advanced time-series prediction techniques, isolating intrinsic oscillator features, and leveraging differential analysis. By addressing these challenges, more robust and reliable authentication methods can be achieved, enabling improved security and performance in wireless communication systems.

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