

Synchronization System Performance Benefits of Precision MEMS Super-TCXOs under Environmental Stress Conditions

The need for synchronization, one of the key mechanisms required by telecommunication systems, emerged with the introduction of digital communication systems. Synchronization requirements have been evolving with technology and adapting to the needs of networks. The tremendous increase of data traffic has triggered the migration from time division multiplexing (TDM) networks to packet networks, in particular Ethernet. This change has provided a cost-efficient means for handling rapidly increasing data loads, but Ethernet is asynchronous in nature and some network services require some form of synchronization.

Synchronous Ethernet (SyncE) is one of the standards developed to enable synchronization in packet networks through physical layer frequency synchronization. SyncE requires hardware support along the entire path of frequency synchronization transfer. Another standard is precision time protocol (PTP) defined by IEEE 1588 that enables frequency, phase and time synchronization through any packet network. Hardware support is not required from a packet network to carry PTP timing, however using PTP aware devices, such as transparent clocks and boundary clocks, may be necessary to achieve required synchronization accuracy.

In both SyncE and PTP applications, the local oscillator is a key component that has a direct impact on the quality of the recovered clock or time. Network devices can be installed in different locations. Some may be in a stable indoor-temperature environment, and others might be mounted in outdoor boxes that are exposed to harsh conditions. Local oscillators must deliver a high-quality, stable reference regardless of environmental factors. SiTime MEMS Super-TCXO[®] (temperature-compensated oscillators) offer significant performance and reliability benefits compared to traditional quartz TCXO solutions when operating under severe and dynamic conditions.

System Performance under Environmental Stressors

Oscillator datasheets guarantee performance specifications under ideal operating conditions including controlled still air environment without any temperature transients of airflow, no vibration, and stable supply voltage. These ideal conditions do not exist in real-world applications and the performance of a TCXO once subjected to these environmental stressors is unknown. A common performance risk mitigation strategy is to remove the stressors.

Some common techniques include:

- Mounting a small plastic cover on the board over the TCXO to isolate it from external airflow.
- Placing the TCXO in a section of the board that is far from high power ICs that generate thermal transients and are away from cooling fans.
- Carefully designing the TCXO power supply which may include using a high quality dedicated LDO.

While considered good design practices for precision quartz TCXOs, these techniques make the design more difficult, restrictive, and expensive. In some cases, applications impose additional restrictions that make it difficult or impossible to eliminate environmental stressors. For example, small form-factor pluggable (SFP) modules have size and power restrictions, which force the oscillator to be placed in a small and hot enclosure with no option for controlling temperature transients. Another example is equipment that must be located near vibration sources, like equipment mounted on poles next to railroad tracks.

A better way to solve the problem is to use an oscillator that is not sensitive to environmental stressors and can maintain the same level of performance regardless of operating conditions. This reduces the risk of performance degradation, simplifies system design, and reduces cost.

Architecture of MEMS Super-TCXO

SiTime MEMS Super-TCXOs are designed to be immune to common environmental stressors such as air flow and temperature transients, shock and vibration, power supply voltage variation, and output load variation.

Figure 1 shows a precision MEMS Super-TCXO block diagram. At the heart of the device is the DualMEMS® architecture. Two MEMS resonators with different temperature characteristics are located on the same silicon die, which ensures almost perfect thermal coupling between the two resonators. One of the resonators is used as a frequency reference to a fractional PLL which generates the output clock signal and the other resonator acts as a temperature sensor.

The PLL has been engineered to provide excellent performance:

- Better than 0.1 ppb resolution (no frequency steps at the output)
- Low phase noise at high frequencies
- Excellent spur performance

The device utilizes a complex multilevel voltage regulator architecture that serves multiple purposes:

- Dramatically reduces sensitivity to external supply variations and power supply noise
- Decouples internal power supply domains to eliminate output spurs

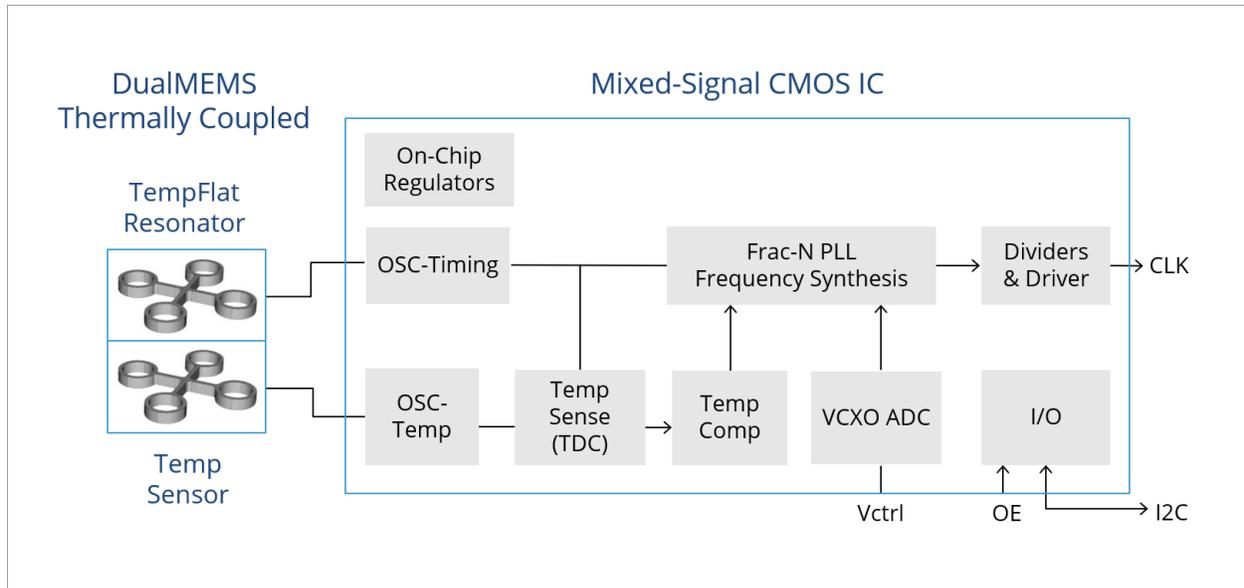


Figure 1: Architecture of precision MEMS Super-TCXO

Reducing Sensitivity to Airflow and Temperature Transients

SiTime MEMS precision Super-TCXOs use a temperature sensor scheme that offers low noise, high compensation bandwidth, and best-in-class temperature measurement resolution of 30 μ K (Figure 2).

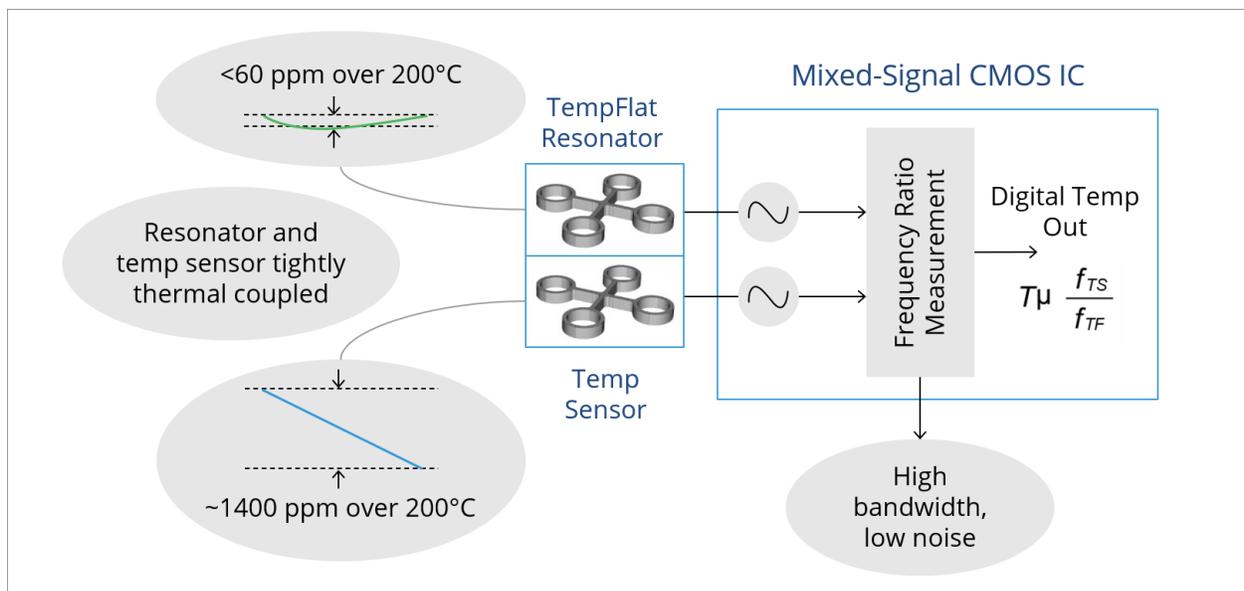


Figure 2: Temperature sensor architecture

Two MEMS resonators reside on the same physical die. One of the resonators is a TempFlat[®] resonator that is designed to have very low sensitivity to temperature variations, with less than 60 ppm frequency change over 200°C. The other resonator is engineered to have first order frequency over temperature response with ≈ 7 ppm/°C slope. The ratio of the two resonators provides a measure of die temperature.

This approach offers the following benefits:

- No temperature gradient between the resonator and temperature sensor even in the case of fast thermal transitions
- No temperature measurement error due to the temperature difference between the sensor and resonator

This DualMEMS® configuration, combined with an ultra-low-noise, high-bandwidth temperature-to-digital converter (TDC) circuit, enable a best-in-class semiconductor temperature sensor and make SiTime Super-TCXO devices insensitive to airflow and rapid temperature transients. This performance can be demonstrated using Allan deviation (ADEV) measurements that show statistical deviation of fractional frequency change over a time interval called averaging time (Figure 3). Under still air conditions, the SiTime MEMS Super-TCXO has slightly better ADEV performance at 1s to 100 s averaging times and is 2.5 times better at 1000 s. The difference in ADEV changes dramatically when the devices are exposed to light airflow (fan in TestEquity 115 Temperature Chamber). There is almost no impact on the SiTime MEMS Super-TCXO, but up to 38 times performance degradation from the quartz TCXO.

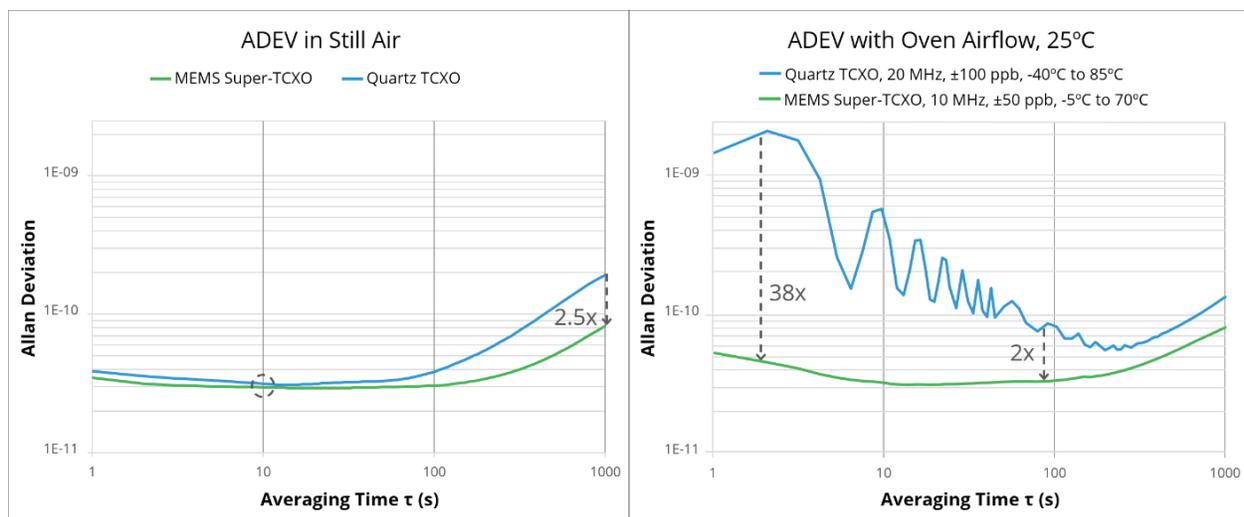


Figure 3: Allan deviation (ADEV) of MEMS and quartz TCXOs without and with airflow

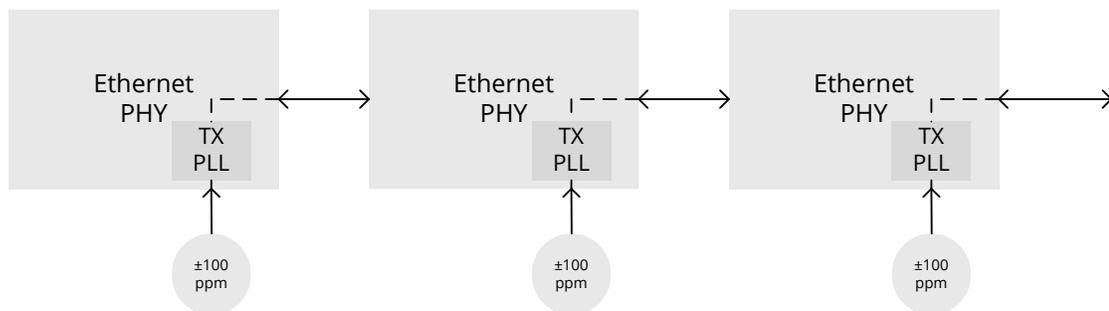
The TCXO frequency slope ($\Delta F/\Delta T$) specification is critical for maintaining a constant output frequency in the presence of airflow and thermal gradients, which is the dominant source of time error in a PTP application. Watch video: [SiTime Elite Super-TCXO Dynamic Performance vs. Quartz TCXO](#) to see a side-by-side test of a MEMS Super-TCXO compared to a best-in-class 50-ppb quartz TCXO. Both devices are simultaneously subjected to environmental stressors such as airflow and thermal gradients, while frequency error and ADEV are measured.

For additional details on the construction and elements of the DualMEMS architecture, and how they differ from quartz TCXOs, see SiTime technical paper: [DualMEMS Temperature Sensing Technology](#).

Synchronous Ethernet (SyncE)

TDM networks, like SONET/SDH require frequency synchronization at the physical layer. Ethernet is asynchronous in nature and is not designed for synchronization transporting. TDM emulation is used to connect asynchronous and synchronous networks, but it requires a synchronized frequency reference. SyncE provides a way to synchronize Ethernet-based packet networks. The requirement of synchronization introduces additional restrictions to the equipment clock.

Asynchronous Ethernet



SyncE

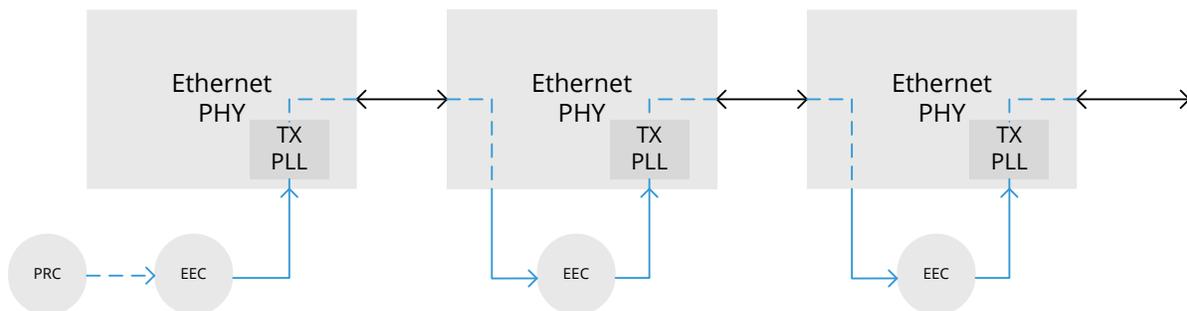


Figure 4: Timing distribution in SyncE

Asynchronous Ethernet requires a ± 100 ppm free running oscillator to clock the transmitter PLL (Figure 4). The clock signal that is recovered through CDR is used only to receive the data and is isolated from transmitter. In SyncE, an Ethernet equipment slave clock (EEC) is used instead of the oscillator to transfer frequency synchronization from the RX and TX, so that transmitted data is clocked with the same frequency that is embedded in the received data. It creates a synchronization chain and all network devices downstream are synchronized to a common reference which is traceable to the PRC. The EEC is a low bandwidth PLL (0.1 Hz to 10 Hz), so it requires a good quality TCXO to limit slow frequency fluctuations called wander.

SyncE Wander Performance Metrics

Wander generation for SyncE clocks is defined as wander appearing at the output of a clock in the absence of input wander (ideal wander free input). Wander generation is a function of both PLL design and local oscillator performance, but for modern high-performance PLLs it is dominated by the TCXO quality.

The maximum time interval error (MTIE) is a measure of the maximum time error of a clock over a particular time interval called observation time. MTIE is defined as the peak time deviation of a clock and therefore is very sensitive to a single extreme value deviation. It is used for bounding transients, maximum wander, and controlling frequency offsets.

Time deviation (TDEV) characterizes the RMS energy of the clock phase noise as measured through a bandpass filter. Filter bandwidth is determined by the observation interval. TDEV specifies spectral content of phase noise. It is useful for limiting the wander that is generated at various frequencies so that it can be filtered by downstream clocks and network wander accumulation can be controlled.

Airflow Impact on TDEV and MTIE

ITU-T standards, in particular G.8262.1 specify wander generation limits (compliance masks) for the SyncE EEC. MTIE and TDEV specification limits are defined for averaging times from 0.1 s to 1000 s or 10,000 s. This is the part of the spectrum that overlaps with the spectrum of airflow and temperature transients. Local TCXO sensitivity to those environmental factors will degrade the performance of the EEC. The clock that passes compliance testing in quiet air conditions may fail or be marginal in the presence of airflow.

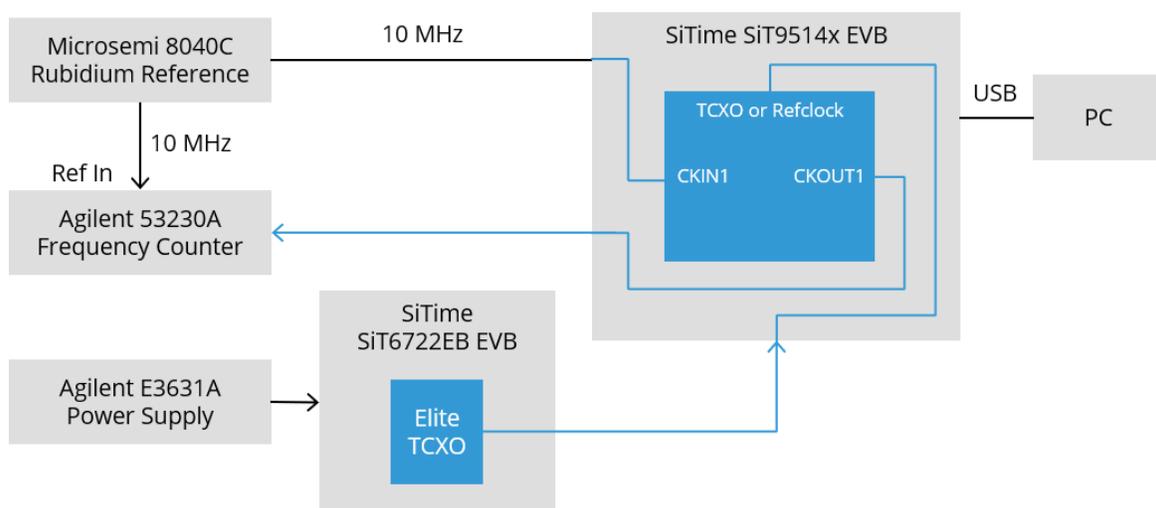


Figure 5: Wander measurement test setup

Quartz TCXOs do not have the tight thermal coupling and fast temperature compensation advantages of SiTime MEMS Super-TCXOs and therefore are sensitive to airflow. This can be illustrated by comparing the wander performance at still air and breezy air conditions. Figure 5 shows the measurement test

setup used for MTIE and TDEV measurements. For this test, a quartz TCXO and MEMS Super-TCXO were paired with a SiLabs Si5328 SycnE PLL. A high quality Microsemi rubidium reference was used as wander free input to the PLL and frequency reference for a frequency counter. To collect MTIE and TDEV metrics, the output frequency of the PLL locked to rubidium was measured for a statistically appropriate amount of time (at least 12 times observation time) and post-processed. For better measurement accuracy, a frequency counter with gap-free measurement capability was used (no dead time between consecutive frequency measurements).

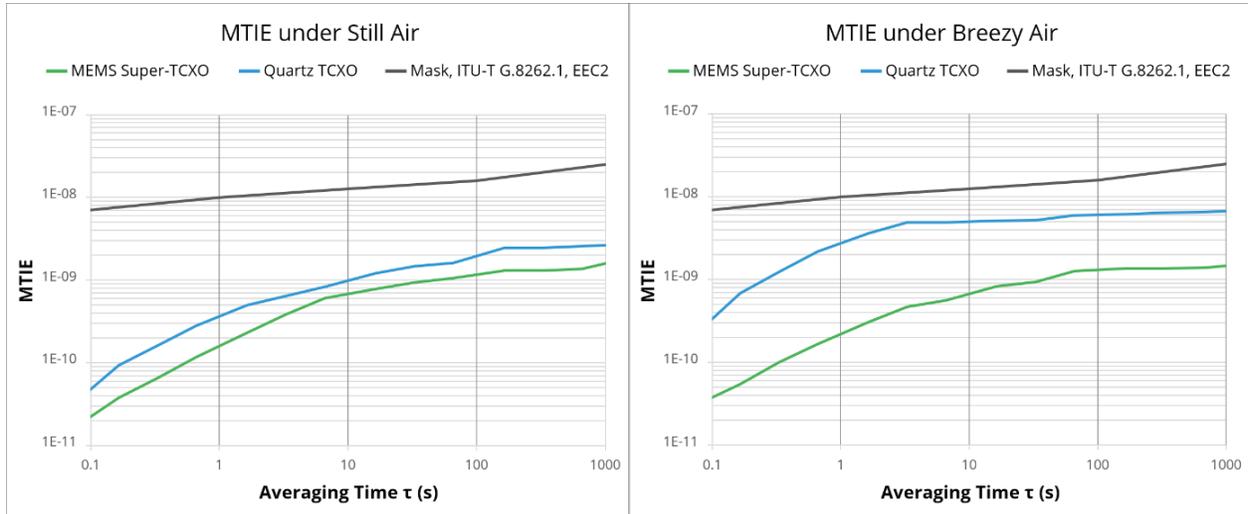


Figure 6: MTIE measurement results without and with airflow

Figure 6 and Figure 7 show MTIE and TDEV measurement results taken for 0.1 Hz PLL bandwidth which corresponds to EEC Option 2 specification. The SiTime MEMS Super-TCXO and quartz TCXO have been tested under two different conditions: 1) still air – stabilized temperature and oscillators well isolated from any airflow with multiple layers of insulation, and 2) breezy air – oscillators exposed to a regular airflow of a TestEquity 115A temperature chamber. As shown in the plots, the wander performance of the MEMS Super-TCXO is not affected by airflow, whereas the quartz TCXO shows significant degradation, 2 to 5 times worse with some averaging times getting close to violating the compliance mask.

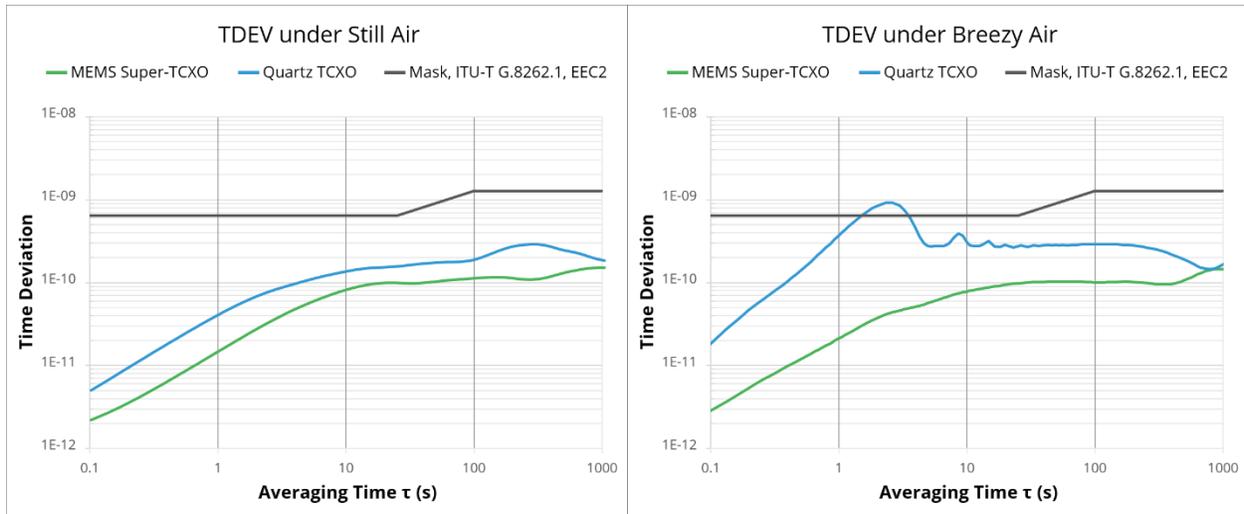


Figure 7: TDEV measurement results without and with airflow

Precision Time Protocol Performance

Precision time protocol (PTP) is a two-way time transfer protocol defined in IEEE 1588 that enables transfer of timing information through a packet network, like Ethernet. Timing is distributed from the PTP master to all slave devices in a network domain by exchanging timestamped messages between the two. One of the biggest challenges in a PTP network is a packet delay variation (PDV) which is a variable delay of packet propagation between the master and slave clocks. It can be caused by a variety of different factors, such as network load variations or network switches running various software algorithms. PDV shows as noise on the recovered time information and has to be filtered (Figure 8).

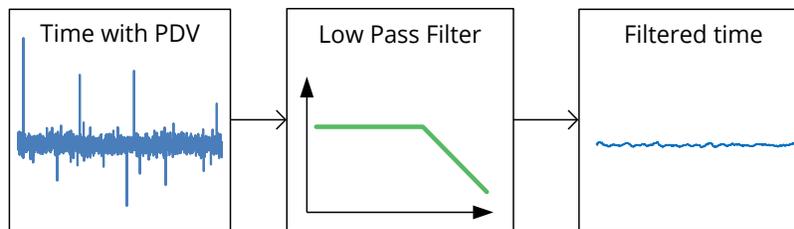


Figure 8: Packet delay variation

Figure 9 shows a high-level model of a slave synchronization loop. The gigabit media independent interface (GMII) provides an interface between the physical layer and MAC. PTP messages are time-stamped upon receipt, usually through immediate hardware timestamping to avoid software delays. One of several PTP packet selection algorithms may be used to preselect the PTP packets that are least affected by PDV. Further PDV filtering is done by a low-pass filter and low-bandwidth servo loop.

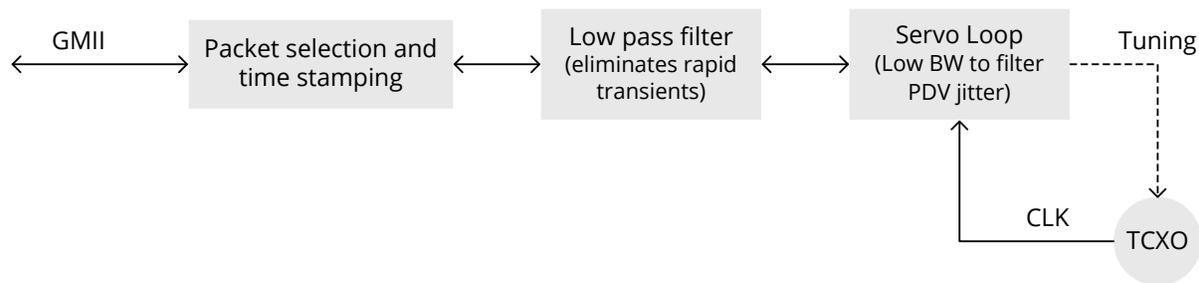


Figure 9: PTP slave synchronization loop

A high-quality local oscillator (TCXO or OCXO) is a critical part of the servo loop. The rate of PTP synchronization messages is typically 8 to 32 messages per second. Some of the messages may be rejected if a packet selection algorithm is used. The local oscillator has to provide timing information between updates. For better PDV filtering, the servo loop bandwidth must be as low as possible, but this puts more pressure on the local TCXO which has to provide excellent stability over longer intervals of time. Oscillator frequency transitions, which may be due to internal noises or external factors like temperature variation, can be tracked only when they are slow enough to be within the bandwidth of the servo loop. Otherwise they directly reflect on the performance of the recovered clock.

PTP Slave Performance in the Presence of Temperature Transients

Time error is a combination of network performance and oscillator noise. The tradeoff between PDV filtering and oscillator noise is defined by servo loop bandwidth. Under normal operating conditions the filtering bandwidth can be set to a very low value in the order of 10 millihertz or below. It provides good PDV filtering capability and excellent PTP performance.

In the real application, it is not always possible to achieve excellent stable environmental conditions. PCB temperature transients may be caused by the variable load of a processor; ambient temperature changes may be caused by cooling fans turning on and off, or service personnel opening the doors of the enclosure; vibration may be caused by passing traffic. The frequency of quartz TCXOs is very sensitive to these environmental factors, and quartz datasheets only guarantee performance under ideal conditions.

Figure 10 illustrates one reason engineers use an OCXO instead of a TCXO in a PTP application. The plot shows a time error between the master and slave that are locked by the means of PTP through Ethernet. At the time $t = 60$ s, hot airflow (about 50°C) is applied to a local oscillator that provides the clock signal to a PTP slave device. A slave device with a quartz TCXO responds with a dramatic degradation of time error performance and significantly violates the 1.5 μ s time error limit. Slave devices with either a SiTime MEMS Super-TCXO or quartz OCXO do not experience any measurable performance degradation.

The MEMS Super-TCXO provides the same airflow and rapid temperature transition performance level of an OCXO for PTP applications.

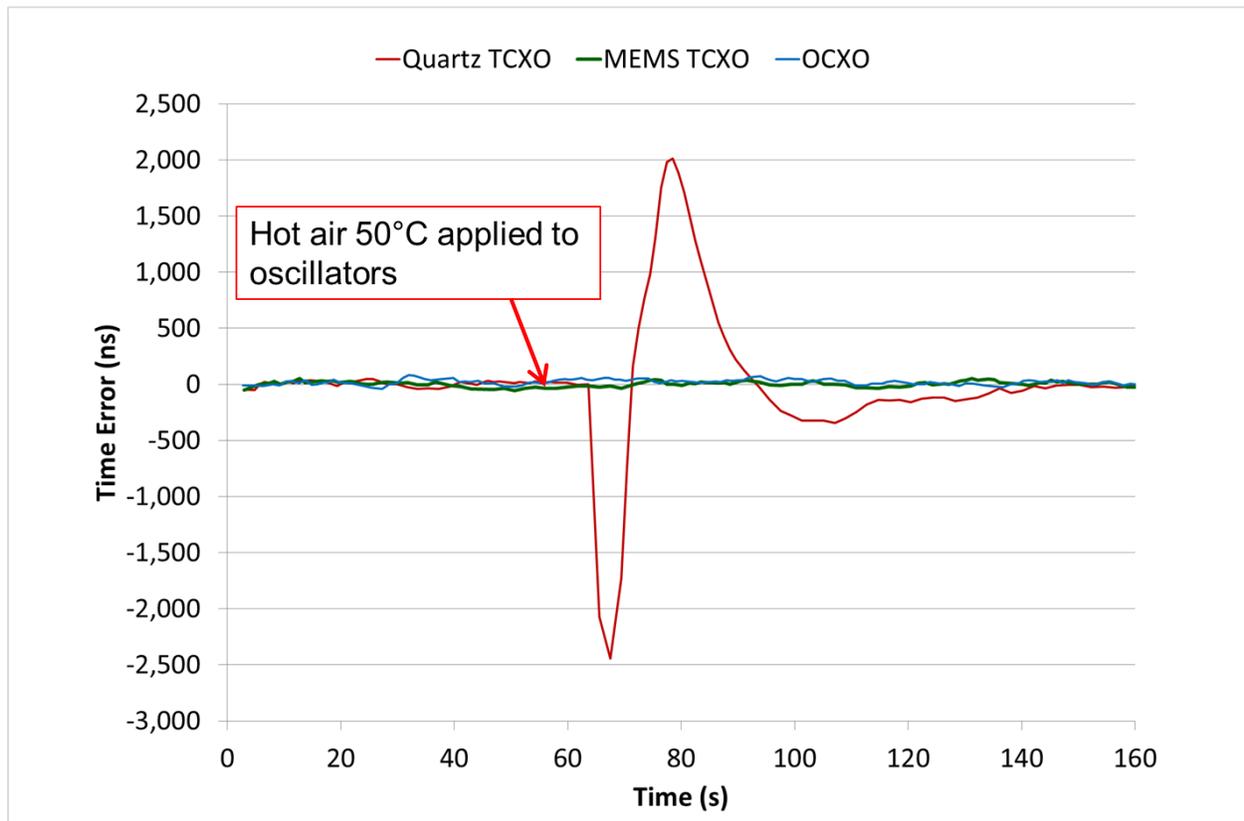


Figure 10: PTP slave performance under temperature transient with various types of local oscillators

Short-term Holdover Performance

Holdover is the state when the PTP slave has lost a connection to the PTP master and is running off the local oscillator. A holdover synchronization loop freezes frequency updates and holds the last-known good value. Short-term holdover may range from a few seconds to a half hour. There can be multiple reasons for short-term holdover:

- A master change occurs when the PTP master has been lost in a network. The condition is triggered when slave devices do not receive announce messages from the master for a certain pre-configured amount of time. At timeout, all PTP devices in a domain (except slave-only devices) start sending announce messages and run a best master clock algorithm (BMCA) to determine the best PTP device to take over the PTP master role.
- A PTP device may not receive any good PTP timing packets consistently or experience significant packet delays due to temporary network disruptions or network traffic congestion.

In both scenarios, this type of holdover time typically ranges from a few seconds to a few minutes. During the holdover, the clock should maintain time error within the required limits. Since the local

oscillator is free running, the holdover performance is a direct reflection of the local oscillator characteristics. Figure 11 illustrates the relationship between oscillator characteristics and time error in holdover.

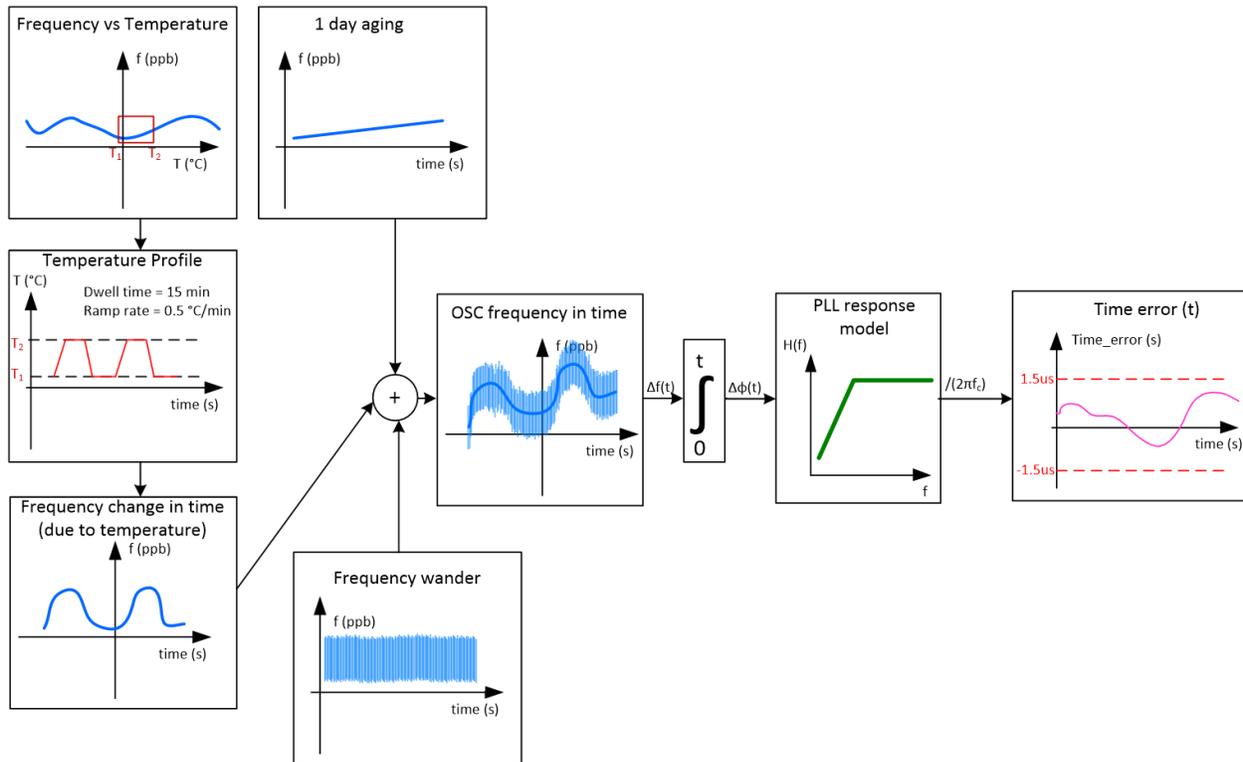


Figure 11: Correlation between oscillator characteristics and time error in holdover

The frequency over temperature characteristic defines how oscillator output frequency will change in time in response to a certain temperature profile. The drift of the oscillator called 1-day or short-term aging determines how frequency drifts in time at a constant temperature. Those two components are referenced to zero-time and summed to get a resulting characteristic of frequency change in time, which is later integrated in time to get phase deviation and converted from radians to time units using a $2\pi f_c$ conversion factor, where f_c is carrier frequency. To complete the picture, random phase noise is converted to time domain and added to the time error function.

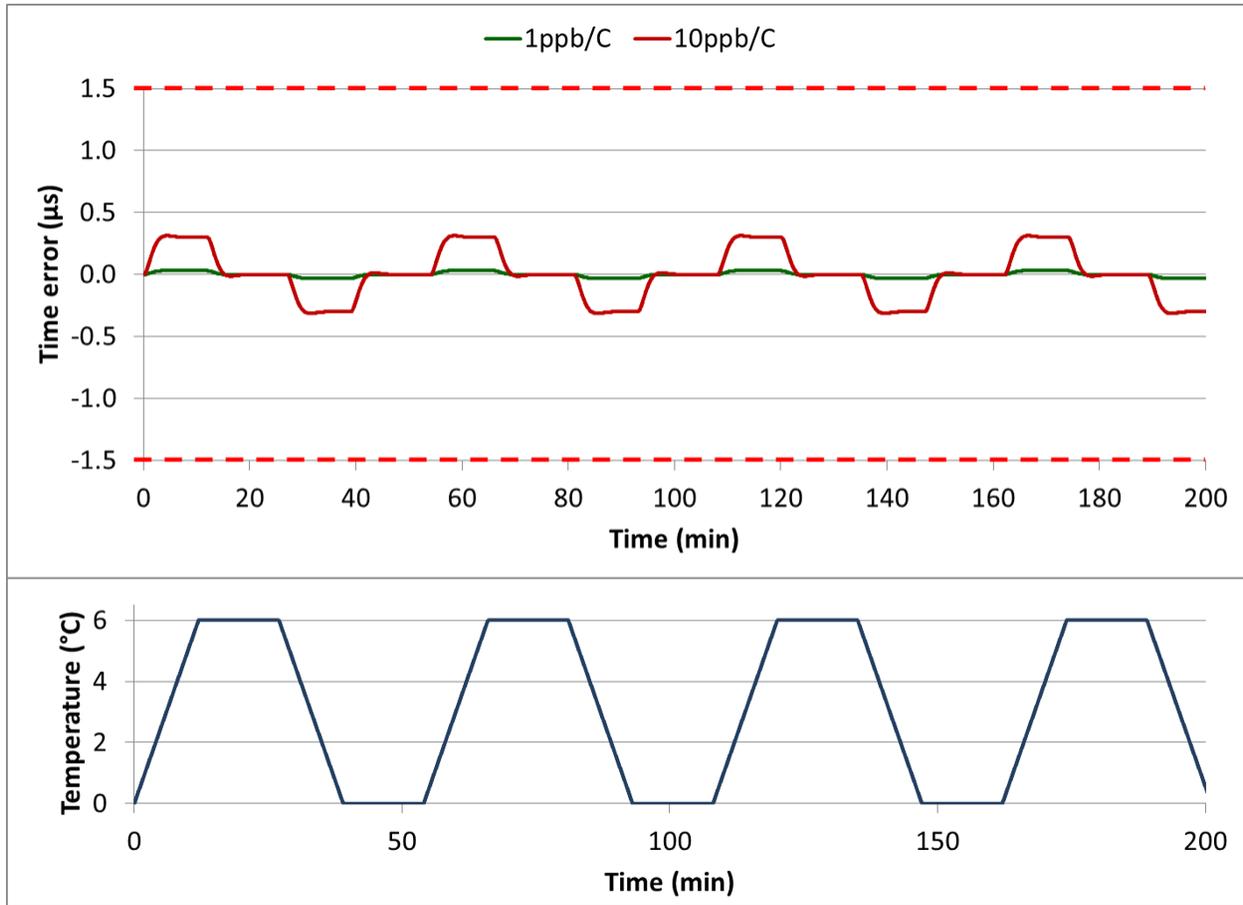


Figure 12: Holdover simulation for different frequency slopes of the oscillator

Short-term aging and phase noise of high-quality TCXOs are negligibly small in context of 1.5 μs holdover specification that is required for many applications, like LTE eNodeB. The main contributor in this case is frequency change due to temperature variation as illustrated in Figure 12. It shows the simulation of time error in holdover caused by a certain temperature profile shown at the bottom. This data suggests that short holdover time, in the presence of a 0.5°C/min temperature ramp that changes the ambient temperature by 6°C in 12 minutes, varies from 3 to 10 minutes, depending on the frequency slope ($\Delta F/\Delta T$) of the oscillator. Since $\Delta F/\Delta T$ by definition is frequency sensitivity to temperature variation, it is a critical specification that determines holdover time.

Figure 13 shows measured $\Delta F/\Delta T$ for various TCXOs including a SiTime MEMS precision Super-TCXO. The SiTime Super-TCXO has been designed with high-resolution seventh order temperature compensation (described on page 3) that results in a well-controlled smooth shape of frequency over temperature characteristic that guarantees OCXO-level $\Delta F/\Delta T$. Temperature changes are limited in the environments in which telecommunication equipment operates; therefore the frequency stability spec over the full operating temperature range is less relevant to application performance. The SiTime MEMS Super-TCXO offers the same level of PTP performance as a ± 10 -ppb OCXO, but has the benefit of lower power, smaller size, and better price.

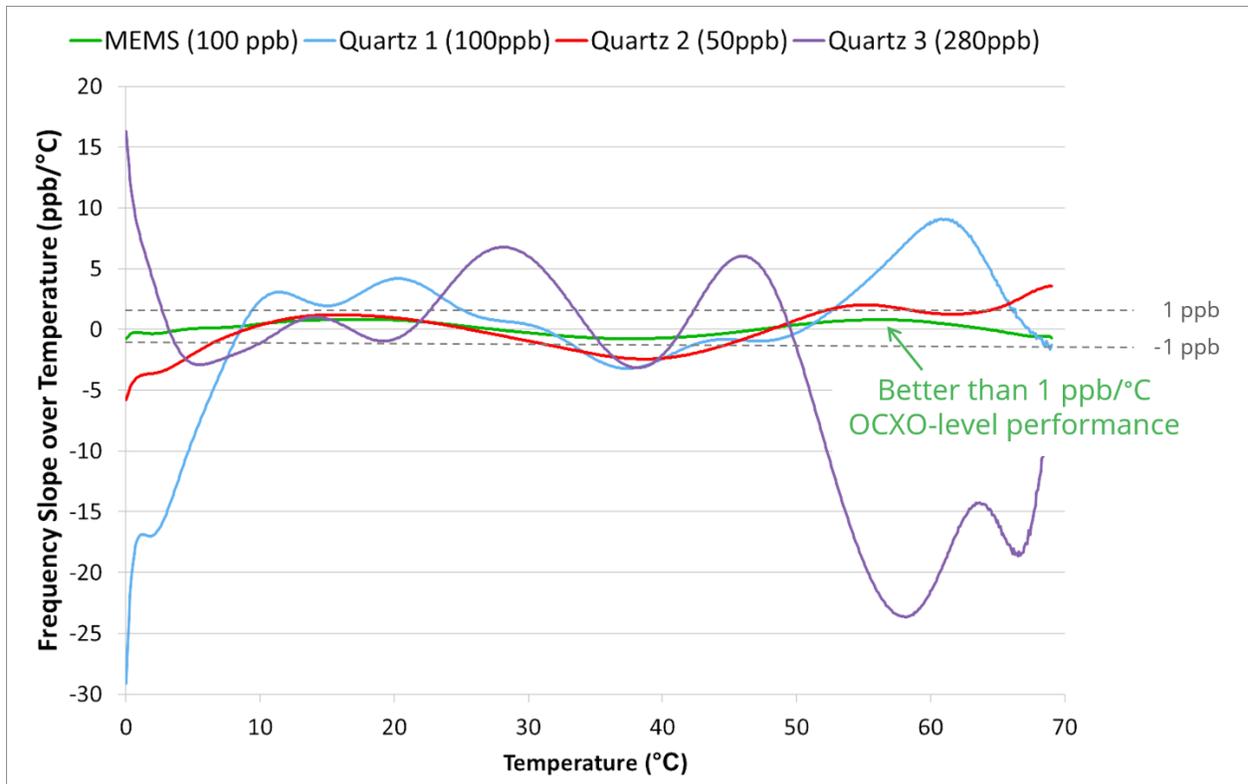


Figure 13: Frequency slope of different TCXOs

Conclusions

Synchronization is one of the most important requirements for telecommunication systems. SyncE and IEEE 1588 are the most common standards used for synchronization in modern systems. Both standards require a good quality TCXO that maintains performance under various environmental conditions. SiTime MEMS Super-TCXOs were designed to solve the environmental sensitivity problems of quartz TCXOs.

Many PTP applications have adopted quartz OCXOs because quartz TCXOs do not provide the same level of frequency slope and airflow sensitivity performance. MEMS Super-TCXOs can now replace quartz OCXOs in these applications. The exceptional robustness of MEMS Super-TCXOs to rapid temperature transients, airflow, vibration, and other external factors makes them an ideal choice for maintaining high performance and good margin in SyncE applications.

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