Lowering the Total Cost of Timing with the Increased Reliability of IC-based OCXOs

White Paper

Abstract

Quartz crystal based oscillators, specifically Oven Controlled Crystal Oscillators (OCXO), continue to dominate applications that require high quality factor and high stability. The complexity of the thermo-mechanical design, the intricacies of manufacturing low profile solutions with reliable discrete components and the laborious testing and qualification process all add cost to an OCXO. The reliability of these devices is extremely challenging since OCXOs operate at high internal temperatures continually over their lifetime. Recent developments in OCXO technology using Integrated Circuits (IC) are breakthroughs in the industry allowing a significant reduction in manufacturing complexity which in turn significantly improves reliability. In addition, IC-based OCXOs reduce the overall size and power requirements compared to traditional discrete OCXO designs.

Introduction of Digital Signal Processing (DSP) techniques is improving OCXO performance by an order of magnitude compared to similar traditional OCXO package profiles. The knowledge and experience in oscillator design over many decades are now being transferred into the digital domain, thanks to the powerful processing engines which make it possible. Residual thermal effects, hysteresis, power supply variations and other system effects can now be compensated while the system is in operation. Ageing of the system, measured against a known reference, can also be corrected on the oscillator level. Support for system level signals like 1 Pulse Per Second (1 PPS) input and output in an OCXO can ease system integration challenges. Such system level support functions save cost and simplify the complexity of characterisation of the equipment (e.g. Temperature Cycling and Ageing characterisation).

A number of applications demand extreme operating temperatures and Oven Control methods have traditionally been limited in achieving such temperatures. Innovative crystal cuts and new thermally insensitive components are being evaluated as potential solutions. There is also development in lower cost Temperature Controlled Crystal Oscillator (TCXO) technology to improve stability. Techniques that are used in the Oven Control methods are being applied in temperature compensation to further reduce the residual effects and achieve performance in a low-power TCXO that is comparable to some higher cost OCXO.

Introduction

Quartz crystal based timing generation technologies continue to dominate the frequency control products industry. This paper looks at recent technological improvements in the oscillator industry and the upcoming innovative trends. The paper introduces new concepts in the technology, architecture, mass manufacturing and testing of OCXOs. Crystal based solutions are now achieving stability levels that could only have been achieved by technologies like Rubidium, thanks to the intelligence that is currently possible to be implemented on the oscillators.

Background: Increasing requirements on Synchronisation

Steered oscillators with specific short, medium and long-term stability performances are used for synchronising network elements as well as terminals in the wired and wireless Telecom and Data communication networks. In traditional networks, the clock recovery and thus synchronisation is based on physical layer, point to point mechanisms and are deterministic. The behaviour of such systems are stationary in nature and filtering such network signals to derive local clocks is relatively straight forward.

With the advent of packet networks, the synchronisation mechanisms have moved on to higher protocol levels. Precision Time Protocol (PTP) and Network Time Protocol (NTP) work on protocol layer, exchanging time stamps as clock signals between master and slave clocks. Timing packets containing time stamps are intended to transverse

Author: Ullas Kumar
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over multiple network elements. These network elements are characterised, in general, by statistical multiplexing of packets to the output queues. Intelligent packet scheduling mechanisms and variable packet length transmissions cause unequal queueing delays and cause variations in packet travel times. Such uncertainties cause packet delay variations resulting in non-stationary signals at the slave network elements. Filtering these signals requires additional processing. A common technique suggested by the Industry Standards is to do a selection of minimal delay packets, use them as representative signals of the network and perform clock recovery on these signals. It is suggested to use windowing methods on arriving timing packets to generate these “lucky” packets for clock recovery.

Traditional network clocks use 0.1 – 10 Hz filtering bandwidths to clean up the network recovered clock. With packet networks, much lower filtering bandwidths are used. For “unaware” networks, (Networks which do not support synchronisation on the Network Elements) bandwidths in the order of 1 mHz or lower are employed. For “fully aware” networks (where every Network Element has synchronisation capabilities) a bandwidth of 0.05 – 0.1 Hz is recommended.

Unfortunately, many telecom and data communication networks today are not ready to support such “fully aware” network structures, unless they are green field implementations. Current networks are a combination of many possible synchronisation elements. Unaware networks, partially aware networks, partially aware networks but with physical layer clocking support, fully aware networks, fully aware networks but without physical layer support, networks that support transparent clocks, transparent clocks without physical layer support and many other complex combinations are possible. Simulations show that in order to support the performance of the equipment clocks suggested today, an ovenized clock is necessary as the local reference clock to the servo mechanism used at the terminal equipment. A packet clock will have an OCXO as the default local reference.

Along with the network elements that carry the traffic from a network, the network terminal is also a focal point. Currently, the objective of synchronisation deployment in transport and access networks is to support cellular base stations as the end terminals and support the delivery of 1.5 µS of time accuracy from the network to the base station. The base stations use different types of synchronisation strategies and the HetNet architecture (co-existence of Macro Base Stations and small cells on the same frequency spectrum) along with TDD (Time Division Duplexing) technology makes the 1.5 µS synchronisation requirement between base stations mandatory. Applications such as location services drive the accuracy requirements to below 100 ns. Although most of the base stations are built to have alternative synchronisation mechanism when the main synchronisation source fails for any reason, robust designs employ local references with ‘holdover’ capabilities to maintain system functionality in the event of short or medium term disturbances. This is particularly true as GNSS technology has become increasingly vulnerable to jamming events. Base stations – at any level of complexity - invariably use an ovenized oscillator as the local reference clock.

Applications such as financial networks, smart power grid networks, wireless sensor networks, video distribution systems, and access technologies such as PON, VDSL/G.FAST and Cable TV networks are adopting PTP as the synchronisation technology. New and upcoming applications that run on these networks are requiring the networks to support synchronisation. Thus, such network elements which used to have free running, relatively loose stability clocks (100 ppm) are now required to support packet clocks and are upgrading to higher stability clocks (<100 ppb). Fortunately, the Frequency Control Product industry is evolving to support cost effective but still high stability oscillator technologies to be able to support the smooth transition of such an adoption.

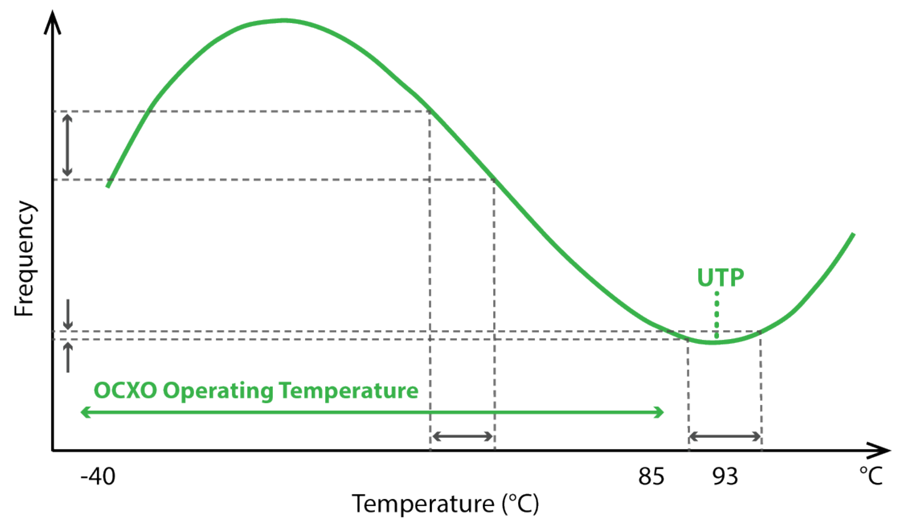
OCXO Technology and Evolution

Frequency instability against temperature variation is one of the key short to medium term stability issues of quartz based crystal oscillators. An oven controlled oscillator uses a temperature-controlled chamber to keep the quartz crystals at fairly constant temperatures to keep the frequency of the oscillator to certain stability levels.

A very basic illustration of the operation of the OCXO is depicted by the Frequency versus Temperature performance graph as shown in Fig. 1.

The turn over points in the temperature response curve gives the minimal frequency variation around the temperature changes, thus the Upper Turnover Point, which is outside the normal operating temperature of the oscillator is often selected as the oven control point.

Fig. 1: Frequency Instability versus Temperature Variation



Thermomechanical design plays an important role in the performance of the oscillators along with the electrical circuits that control the oven and compensates for various residuals. Typical values of 0.1°C to 0.01°C change in the oven are expected to an environmental change of 125°C, for example.

Reliability Challenges

The components inside the oscillator oven are subjected to continuous heating for the entire life of the product. This is especially true of devices in telecom equipment that keep running round the clock, every day of the year. Therefore, the typical environments in which an oven in a telecom or data communication system resides are much harsher and electrically demanding than components used in the automotive environments (that may only be operational for 10% of their normal lifetime).

Such harsh environments bring challenges of reliability issues. In order to combat the environmental challenges, OCXOs are typically designed with discrete electronic components. A typical oscillator at 10 ppb frequency stability over temperature could easily have more than 100 components and at least double the number of solder joints. Such devices, when mass produced, result in FIT rate (failures per billion hours of operation) in the range of 1000 – 1500. This high value, more than an order of magnitude higher than many complex silicon devices, places discrete OCXOs alongside power supplies and fans as one of the largest contributors to the overall FIT rate of many telecom boxes.

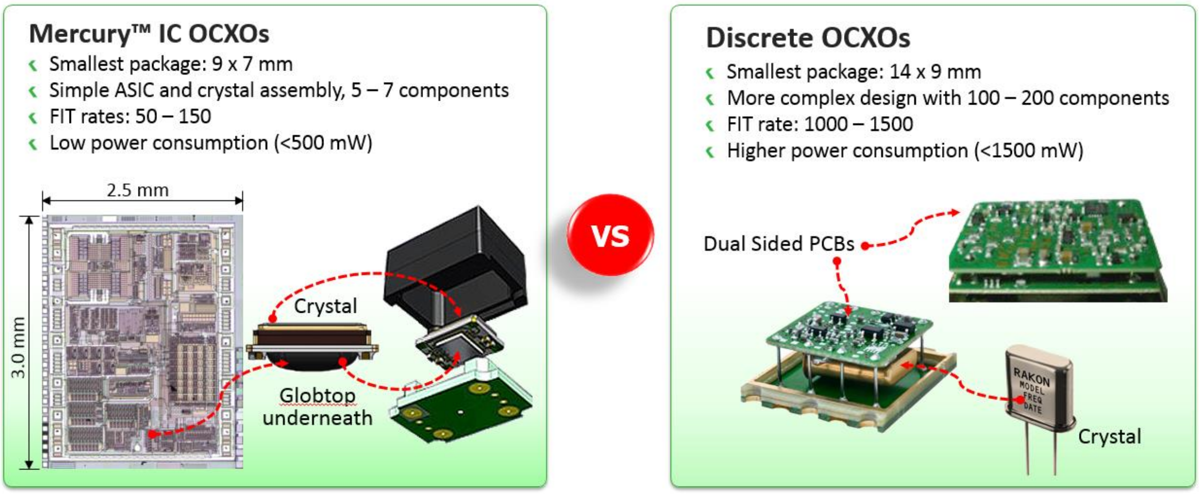
For most telecom systems, equipment service requests are a meaningful portion of the Total Cost of Ownership (TCO) for the carrier. A key contributor to the service requests of network equipment are issues related to synchronisation and are driven primarily by the reliability of the OCXOs. Thus, any potential opportunities to improve the reliability of OCXOs will have a direct impact on the TCO.

Monolithic Solutions: IC-based OCXOs

The oscillator industry has started to see Integrated Circuit based OCXOs in recent history. IC-based OCXO solutions integrate the discrete components in the OCXOs as a monolithic circuit. Such a solution immediately brings down the complexity of assembly, manufacturing and testing of the oscillators. The assembly process can be automated as well as the testing of the oscillator devices. The biggest benefit is the reduction in the component count from 100 to below 5, and thus the Failures In Time (FIT) rate improves by orders of magnitude.

There are many other benefits that are realized as the oscillators move to IC-based platforms. The move towards digital domain processing and integration enables the required functions to be realized in lower power and lower profiles compared to analog platforms. Thus IC-based solutions bring in the advantages of lower power compared to discrete solutions. Many terminal equipment designs, even from the carrier equipment perspective, are moving towards Power over the Ethernet (PoE) concept (End equipment terminal powered over Ethernet rather than independent power supply through built in or wall adapters) and there is drive to minimize the contribution of power consumption from each component to reduce the overall power consumption in the system. At similar stability levels of 10 ppb, IC-based solutions bring the power down by a fifth of what is normally consumed by a discrete solution.

Fig. 2: IC-based OCXO versus Discrete OCXO



Integration makes it possible to have smaller sizes as well as lower profile. The lower profile devices allow the solutions to be as compact as possible. Compared to the standard solutions of 25 x 22 x 11 mm sizes at 10 ppb, these new solutions offer 9 x 7 x 6 mm size, which is a tenth of the volume reduction. Such profiles enable new technology options to be possible – an example of which is OCXOs inside a Small Form-Factor Pluggable (SFP) module creating synchronisation solutions which were not imaginable without such form factors of stable references.

The lead time of OCXOs is notoriously long because of the production process associated with the devices. In any production facility, the "Work In Progress" inventory is kept minimal as to produce the components just in time. Considering the production cost of OCXOs, a very close interaction of the consumer and the supplier could still only result in lead times of 12 to 16 weeks considering the assembly, manual tuning, post production ageing and conformance testing processes. Integrated OCXOs can improve the overall lead time because of reduced manufacturing and manual tuning requirements.

Discrete Vs Monolithic solutions

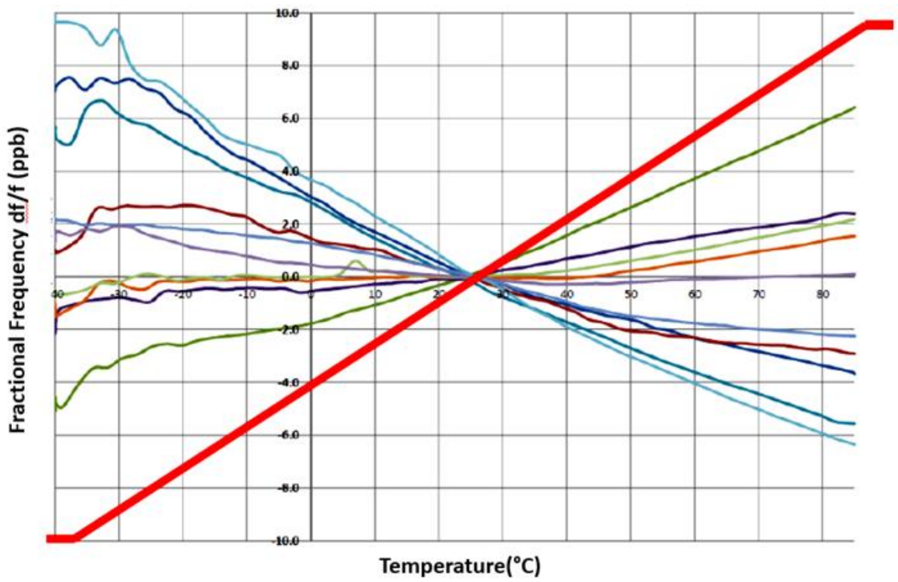
A comparison of discrete OCXOs versus monolithic based solutions is described in the below table.

Features	Discrete OCXO	Monolithic OCXO
FIT (Failures In Time)	>1500	<100
Footprint	25 x 22 mm	9 x 7 mm
Power (steady state)	1.5 W	300 mW
Component Count	> 100	5 to 7
Lead time	16 to 26 weeks	8 to 12 weeks
Volume	6000 mm^3	600 mm^3

Self-Compensation Techniques and Ageing Compensation

Temperature effects and ageing are the two key contributing factors to frequency instability within an oscillator. Traditionally the oscillators are tuned around the turn over point and the performance of the oscillators depends on the crystal's Frequency versus temperature performance at that point. The following chart illustrates the behaviours of randomly selected oscillators of the same category. The bright red line is temperature, ramping from -40°C to + 85°C.

Fig. 3: 12.8 MHz SMD OCXO Stratum 3E Compliant
(response over -85°C to 40°C, 1°C/mn rate temperature scenario)



The use of digital signal processing techniques in oscillators enables real-time compensation against residual errors. Such errors include the residual effects of temperature, ageing, hysteresis, power supply effects and so on. The oscillators are thermally cycled and characterised to extract their thermal behaviours which are used in real-time to compensate at various temperature points. Research is ongoing to implement "deep learning" like approaches to compensate for the oscillators, considering the wide number of variables involved in the process.

Thermal Isolation Challenges

It is always possible to compensate for the changes in temperature, however, the primary challenge is to maintain thermal isolation between the environment and the crystal. The temperature range seen by the crystal needs to be minimal in all possible operating scenarios. Extensive thermal simulation is required to rightly align the crystal and associated components for best heat transfer from the heater to the crystal and maximum thermal isolation between the environment and the heater.

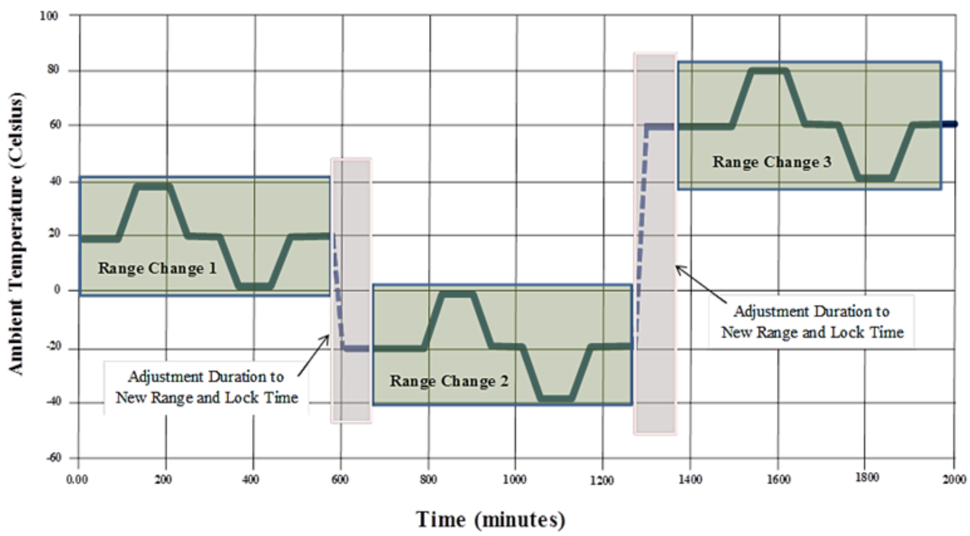
State of the art quartz based solutions are able to provide temperature performances of 0.5 ppb over operating temperature ranges and are able to perform phase holdover of 1.5 µS for more than 24 hours for smaller operating temperature windows such as 10 degrees. Additionally, oscillator modules can be designed to include a 1 PPS input from a GNSS (or another timing source) solution which is then used to both steer the crystal on the frequency and provide compensation values for the crystal ageing effects. These modules can then output both an on time 1 PPS and an on frequency, low noise RF signal which eases system design by reducing the need for additional VCXOs, PLLs and tuning circuitry. Furthermore, by integrating all of these functions into an ovenized enclosure, certain temperature effects in the tuning and PLL circuits are reduced which can enable further performance improvements.

Environmental Challenges and Mitigation Strategies

As described in the previous sections, in OCXOs, ovenized crystals are held at constant temperatures supported by thermo-mechanical constructions to protect against external temperature effects. The ovens are highly sensitive to the ambient temperature changes and airflow around them.

To a certain extent, system understanding and best design practices can improve the performance of the OCXOs and thus can save on the overall component cost. Knowledge about the end application synchronisation requirements, oscillator temperature characterization profile information, other system information such as airflow speeds and patterns will help to select the right OCXO for the application. By combining proper OCXO selection and closely following recommended design practices, one can achieve higher performance results at lower costs.

Fig. 4: Temperature Test Profile



Author: Ullas Kumar
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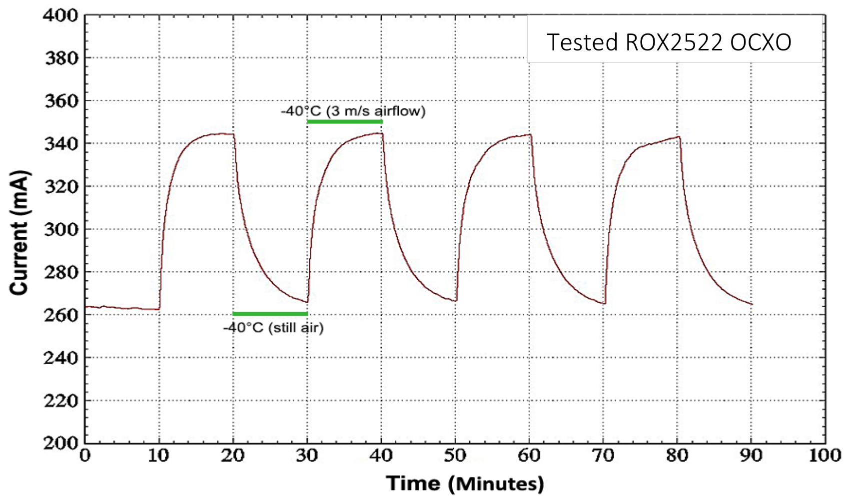
Current synchronisation performance testing is conducted with reference to parameters defined in standards like ETSI EN 300 019-2-3 V2.2.2 and IEC 60068-2-14. These references are primarily focused on testing equipment over complete temperature ranges or rugged temperature cycling. In general, such variations are unlikely to be seen during one real-life cycle of variations, for example, the maximum variation of temperature could be ±20°C in a day, even though the operating range of the equipment is -40°C to +85°C. Because temperature related effects can be significant for the type of oscillators used in telecommunications and thus the associated cost, a constrained temperature range of operation is proposed in standards as synchronisation testing profiles. An example of a proposed synchronisation testing profile is shown in Fig. 5.

Air flow conditions have similar effects on the performance of the OCXOs. The airflow is perceived as change in temperature by the crystals. An OCXO tested at -40°C on still air would not behave the same when tested with a 3 m/s airflow at same temperature conditions. To illustrate the effects of airflow, the following graph shows the power supply current variation in an OCXO (which in turn is an indication of temperature change experienced by the OCXO) at still air and under airflow condition. The airflow impacts the OCXO as temperature change.

The results shown are from testing a Stratum 3E level of OCXO 'ROX2522' in a 25 x 22 x 23 mm package. The graphs show that the airflow varied from 0 to 1 m/s, 10 minutes on and 10 minutes off. Over this rest period, the change in frequency is about 1 ppb and the change in current is about 80 mA. This equates to about a 24°C change in temperature.

Fig. 5: Effect of Airflow on Current Supply

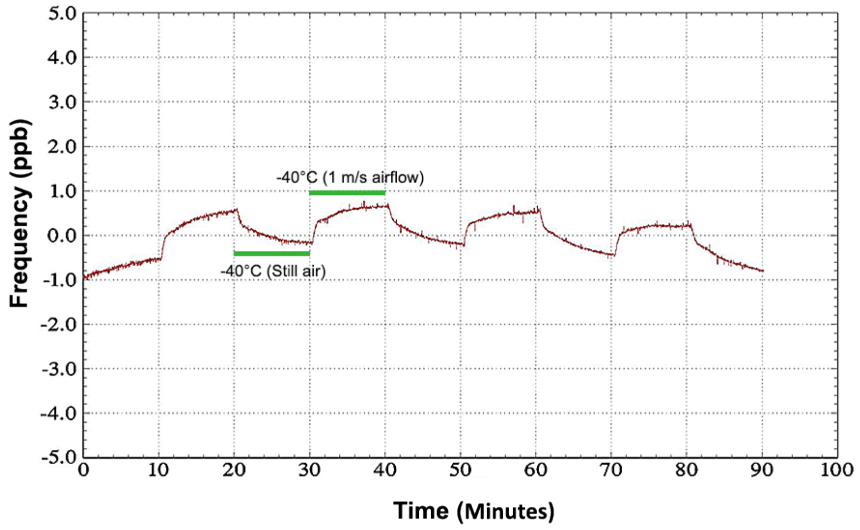


The equivalent frequency change of the device is illustrated in the graph as shown in Fig. 6.

The example shows the impact that is introduced by the airflow on a certain implementation of the OCXO.

The OCXOs are generally defined to have their performances at still air. If the OCXOs are deployed into situations where there are airflows, then such situations need to be characterised and the proper OCXO devices need to be selected.

Fig. 6: Effect of Airflow on Frequency



For best environmental design practices, the physical positioning of the OCXO is very critical. It is recommended that the OCXO be placed at a location where airflow and temperature effects are absent or minimal. Today's complex systems contain processors and System-on-Chip (SoC) that generate heat depending on the loading on the processors. Such heat fluctuation near an OCXO needs to be avoided. Similarly, variable speed fans circulate air in very complex flow patterns to remove heat out of the systems. OCXOs needs to be protected from such flow paths as well. If such a situation is not possible, a plastic or metal cover may be placed over the OCXO. It is recommended that the cover leaves an air-gap of at least several mm above and around the oscillator. The enclosure acts as a shield and the temperature that is being tested can be "the surface temperature of a thin, highly conductive isothermal enclosure surrounding the device with known dimensions". The isothermal surface provides a medium to conduct the heat into the device under test without direct airflow. The isothermal surface may be dimensioned to reflect the dimensions of the customer's enclosure if this is known. Such a procedure will ensure that the synchronisation testing is done under uniform environments and results obtained are under common test conditions.

Summary

Quartz based oscillator technology will continue to dominate as stable sources of reference clocks in the wired and wireless telecom and data communication industry for the coming years. There have been significant advancements in the oscillator industry in recent years. Improved reliability, higher stabilities, lower power and lower profiles have been possible with the introduction of Integrated Circuit based designs and the introduction of Digital Signal Processing techniques. Technology advancements have made it possible to have lower costs for synchronisation solutions. Now there is more choice for designers to select reference clock oscillators from a wide range of stabilities, temperature ranges, sizes and power consumption levels, at the right price levels as desired.

To find out more about how your business can gain lowering the total cost of timing with the increased reliability of IC-based OCXOs, please contact your nearest Rakon Sales office to speak with application experts or simply send an email to sales@rakon.com.

References

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