Emerging Applications Requiring Precision Time and Frequency

M. Bloch, D. Léonard , O. Mancini, T. McClelland,
Frequency Electronics, Inc.
55 Charles Lindbergh Blvd.
Mitchel Field, NY
martinb@freqelec.com, dleonard@gillam-fei.be, oliem@freqelec.com, tomm@freqelec.com,

Abstract - **Numerous commercial and military applications utilize precision quartz oscillators and/or atomic frequency standards to generate super-accurate frequencies and time signals crucial to system performance. Examples where precise time and frequency is essential are telecommunications, drilling for natural resources, synchronizing railroads, satellite ground stations, laboratory standards and various others. In military applications precise time and frequency is essential for synchronizing communications, for radar applications, for emitter locators and other.**

In this paper, we will present precision quartz oscillator and/or rubidium vapor atomic oscillator applications as well as data that demonstrates achieved performance for synchronizing DVB-T, UMTS-FDD, TDD, WiMAX and LTE communications, for seismic methods while drilling for natural resources in challenging environments, for beam-forming in satellite ground stations, for synchronizing military communications that require time errors less than 500ns in 24 hours holdover during severe temperature changes and for various other applications.

I. Introduction

During the implementation of second generation mobile telephony, synchronization needs were not very substantial. It was not required to have a time reference and the requested frequency accuracy was easily achieved.

However, with the implementation of CDMA and especially with the emergence of OFDM in SFN networks a much more significant time and frequency accuracy is required. GPS systems have satisfied this requirement. These equipments use precision quartz and/or rubidium oscillators which successfully fulfill the need for precision time and frequency. Other emerging applications and/or enhancements of existing applications that require precision time and frequency include:

- UMTS – FDD – TDD
- DVB-T SFN
- WiMAX
- LTE
- Clocks For Oil and Gas Exploration
- G (acceleration) compensated oscillators for unmanned air vehicles (UAV), helicopters, fixed wing aircraft and military track vehicles
- Precision signal sources in Earth Stations to provide a stable frequency reference signal for the network

Each of the above applications will be explained and a description of the oscillators pertinent to each application will be presented.

II. UMTS UTRA/FDD

In UTRA FDD, the transmission occurs continuously for uplinks and downlinks on two frequency bands separated by 190 MHz. Allotted bands are 60 MHz wide and are centered on 1950 MHz for the uplink and on 2140 MHz for the downlink. In these bands, the separation between carrier waves is 5 MHz and the multiple access technique is type FDMA/CDMA. The transmission is realized in spread spectrum. Two types of spreading codes are used :

1. Walsh-Hadamard orthogonal codes to identify users in a cell. They are called "channelization codes"; the length of these codes is variable and depends on the type of service.
2. Gold codes (scrambling code) whose role consists in limiting the interference coming from neighbouring cells; each cell is identified by its Gold code in the downlink while each user has a different Gold code in the uplink.

Gold codes have good inter-correlation properties. That's the reason why no time constraint is imposed on the base stations that can transmit in a fully independent way. As a consequence, the synchronization of base stations in a radio access system based on the UTRA FDD technology is currently optional.

In UTRA FDD, two types of channel coding are used: convolutional coding 1/2 or 1/3 when desired error rate is about 10E-3 and turbo coding 1/3 for lower error rates.

<u>In the downlink</u>

Per user, there is only one channel called DPCH which can be considered as time-division multiplexing of a DPDCH data channel and a DPCCH control channel.

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Transmission is realized by frames of 10ms (38400 chips). The chip rate is 3.84Mchip/s. Each frame contains 15 slots of 0.666ms (2560 chips). There are 1501.5 slots per second. Each transmitted bit must be spread by a complete sequence of the channelization code of SF length (Spreading Factor). In the downlink, SF can range from 4 to 512. The number of bits per slot is 5120/SF. We note that the length of the channelization code allows to make the bit rate variable. If SF is 4 the bit rate is 1920 kbit/s and if SF is 512 the bit rate is 15kbit/s. The modulation is realized in QPSK.

In the uplink

Transmission is realized in HPSK.
There are two types of physical channels in the uplink : DPDCH (data channel) and DPCCH (control channel). There can be 0, 1 or several DPDCH and still only one single DPCCH. Transmission is realized by frames of 10ms (38400 chips). The chip rate is 3.84Mchip/s. Each frame contains 15 slots of 0.666ms (2560 chips). In the uplink, SF can range from 4 to 256. If SF is 256, there are thus 10 data bits per slot of 2560 chips, that is a total of 15kbit/s. If SF is 4, there are 640 data bits per slot, that is a total of 960kbit/s. We note that the length of the channelization code allows to make the bandwidth vary. The SF is always 256 for the DPCCH ; however it can vary from one frame to another for the DPDCH.

The DPDCH is transmitted with a lower amplitude than the DPCCH. We have thus two signals with a different amplitude, spread by different channelization codes, to be transmitted. For this purpose, a HPSK modulator is used. Channels I and Q of this HPSK modulator modulate two carrier waves in quadrature. The aim is to build a pseudo QPSK signal whose PAPR (Peak-to-Average Power Ratio) is lower than for a standard QPSK modulation.

III. UMTS UTRA/TDD

In UMTS UTRA/TDD, the transmission and the reception are realized on a same frequency band of 5MHz at differents moments. Bands allotted to the TDD are in Europe from 1900 to 1920 MHz and from 2010 to 2025 MHz. Transmission is realized in QPSK. UTRA/TDD technology is more appropriate for asymmetrical traffics and for internal environments with restricted mobility.

UTRA/TDD technology combines multiplexing by distribution of codes and multiplexing by distribution in time. CDMA technology used in UTRA/TDD is similar to the one used in UTRA/FDD. However, multiplexing between both tranmission directions is temporal. Transmission is realized by frame. Each frame consists of 15 slots. Each slot is characterized by a transmission direction. In addition, each slot is shared between N users. That's the reason why it's necessary to synchronize base stations in a UTRA/TDD radio network to limit intercellular interference. It's not easy to manage this interference problem because, on one hand, near cells can be exploited by different operators and, on the other hand, the slots of a frame can be either in TX or in RX according to traffic needs and without coordination from one cell to the other. Cyclic prefix between two slots is minimum 96 chips, that is 25µs. Time reference must be at least 10 times better.

IV. DVB-T SFN

Digital terrestrial television uses OFDM modulation. The principle of this modulation consists in distributing a broadband bit stream on a large number of « orthogonal » carrier waves (from several hundreds to several thousands) carrying each a low bandwidth. Each carrier wave can be modulated in QPSK or in QAM (16 or 64). In real reception conditions, signals coming from multiple path add to the direct signal and mean that orthogonality conditions between carrier waves are not respected anymore, which results in the presence of intersymbol interference. This problem is solved by making each symbol preceded by a cyclic prefix (CP) during which a copy of the end of the useful symbol is transmitted.

The table below summarizes the different parameters that can be selected by the operator to configure the transmitter.

TABLE I. *DVB-T Parameters*

	8k	**2k**
Number of carrier waves	6817	1705
Number of useful carrier waves	6048	1512
Duration of useful symbol	896µs	224µs
Spacing between carrier waves	1116	4464
Cyclic prefix 1/4	224µs	56µs
Cyclic prefix 1/8	112µs	28µs
Cyclic prefix 1/16	56µs	14µs
Cyclic prefix 1/32	28µs	7µs

In addition each carrier wave can be modulated in QPSK, in 16-QAM or in 64-QAM and the efficiency of the convolutional code can be parameterized to ½, 2/3, ¾, 5/6 or 7/8.

In 8k mode, the long symbol period combined with the large cyclic prefix (1/4 or 1/8) authorizes a satisfactory reception even if very long echos are present. This allows to create large coverage networks with single channel (Single Frequency Network or SFN). A good frequency and time synchronization is essential in a SFN network to avoid interference with neighboring transmitters. Frequency error on carrier waves must be limited to a few Hz and time error must be limited to 1/10 of the cyclic prefix. Concerning frequency and time reference of the transmitter, Reference [5] proposes an accuracy of 10E-9 for the frequency and ±1µs for the pps.

V. WIMAX

The main features of IEEE802.16-e/WiMAX technology are the following :

- Carrier frequency from 2 to 11 GHz for NLOS (non line of sight) and 10 to 66 GHz for LOS.
- OFDM. The 802.16 is mainly built on Orthogonal Frequency Division Multiplexing transmission technique known for its high radio resource use efficiency.
- Duplexing TDD and FDD or TDD only.
- Data rates. A reasonable number is 10Mb/s but reports have given more ambitious figures going up to 70Mb/s or even 100 Mb/s.
- Distance: up to 20km.
- Mobile stations are possible: IEEE802.16**e.**
- MIMO (Multiple Input Multiple Output) and AAS (Adaptive Antenna System).
- MBS (Multicast and broadcast services) feature.
- Topologies PMP (Point to Multipoint) or Mesh.
- Advanced IP architectures significantly reduce network cost.

Four modulations are supported by the IEEE802.16 standard: BPSK, QPSK, 16-QAM and 64-QAM. WiMAX uses the OFDMA principle for multiple access. In WiMAX-OFDMA, the subcarriers are divided into subsets of subcarriers, each subset representing a sub-channel. A user will have a time and a sub-channel allocation for each of its communications. Moreover, the OFDMA WiMAX is scalable; the scalability is the change of the FFT size and the number of subcarriers. The change in the number of subcarriers, for a fixed subcarrier spacing, provides for an adaptive occupied frequency bandwidth and, equivalently, an adaptive data rate.

For both the uplink and downlink, the subcarriers are allocated according to one or another OFDMA permutation mode. Diversity permutations minimize the probability of using the same subcarrier in adjacent sectors or cells. For contiguous permutations, channel estimation is easier as the subcarriers are adjacent.

For OFDM and OFDMA PHY layers, 802.16 defined the following values for the guard interval (or Cyclic Prefix): ¼, 1/8, 1/16, 1/32. For the mobile WiMAX, the value 1/8 is mandatory. The FEC encodings are: concatenated Reed-Solomon Convolutional Code, convolutional turbo codes or block turbo coding. Transmission parameters (FEC and modulation type) can change dynamically. Concerning the duplexing, both TDD and FDD are possible. In an FDD system, the uplink and downlink channels are located on separated frequencies. A fixed duration frame is used for both uplink and downlink transmissions. In a TDD system, the uplink and downlink transmissions share the same frequency but they take place at different times. A TDD frame has a fixed duration and contains one downlink and one uplink sub-frame. The TDD framing is adaptive in that the bandwidth allocated to the downlink versus the uplink can change. The frame duration is decided by the BS between 2.5 to 20ms. In a frame, the TX-RX transition gap between the downlink data and the uplink data can be as small as 5µs.

Globally, WiMAX multiple access is extremely flexible and it is thus difficult to settle universal rules for synchronization. However, IEEE802.16-2004 indicates that there are three options for synchronization.

- Asynchronous configuration. Every BS uses its own permutation. The frame lengths and starting times are not synchronized among the base stations. This configuration can be used as an independent low-cost hot-spot deployment.
- Synchronous configuration. All the BSs use the same reference clock (e.g. by using GPS). The frame durations and starting times are also synchronized among the BSs but each BS may use different permutations. Due to time synchronization in this scenario and the long symbol duration of the OFDMA symbol, fast handovers as well as soft handovers are possible. This configuration can be used as an independent BS deployment with a controlled interference level.
- Coordinated synchronous configuration. All the BSs work in the synchronous mode and use the same permutations. An upper layer is responsible for the handling of sub-channel allocations within the sectors of the base station, making sure that better handling of the bandwidth is achieved and enabling the system to handle and balance loads between the sectors and within the system.

MBS: Multicast Broadcast Services (MBS) may be required when multiple MSs (Mobile Station) connected to a BS (Base Station) receive the same information or when multiple BSs transmit the same information. The mobile WiMAX system supports MBS as an optional feature for the BS. A multi-BS MBS operation requires time synchronization.

VI. LTE

Compared to the UMTS, a fundamental objective of the LTE is to offer higher data speeds for both down and uplink transmission. LTE is also characterized by reduced packet latency.

The key characteristics of LTE are summarized here:

- Enhanced air interface allows increased data rates: the air interface for LTE combines OFDMA-based modulation and multiple access scheme for the downlink, together with SC-FDMA for the uplink. The downlink is specified for single input single output (SISO) and multiple input multiple output (MIMO) antenna configurations.

- Peak download rates of 326.4 Mbit/s for 4x4 antennas, 172.8 Mbit/s for 2x2 antennas for every 20 MHz of spectrum.
- Peak upload rates of 86.4 Mbit/s for every 20 MHz of spectrum.
- LTE supports flexible carrier bandwidths, from 1.4MHz up to 20MHz as well as both FDD (Frequency Division Duplex) and TDD (Time Division Duplex).
- Reduced latency: by reducing round-trip times to 10ms or even less, LTE delivers a more responsive user experience.
- At least 200 active users in every 5 MHz cell. (i.e., 200 active data clients).
- Optimal cell size of 5 km, 30 km sizes with reasonable performance, and up to 100 km cell sizes supported with acceptable performance.
- Co-existence with legacy standards (users can transparently start a call or transfer of data in an area using an LTE standard, and, should coverage be unavailable, continue the operation without any action on their part using GSM/GPRS or UMTS.
- Supports MBSFN (Multicast Broadcast Single Frequency Network). This feature can deliver services such as Mobile TV using the LTE infrastructure.
- All IP based core network with a simplified architecture and open interfaces.

Downlink

LTE uses OFDMA for the downlink. In OFDMA, users are allocated a specific number of subcarriers for a predetermined amount of time. These referred to as physical resource blocks (PRBs). PRBs have both a time and frequency dimension. Allocation of PRBs is handled at the base station. LTE transmissions are segmented into frames, which are 10ms in duration. Frames consist of 20 slot periods of 0.5ms. Sub-frames contain two slot periods and are 1.0ms in duration. The modulation parameters are summarized in the table below:

TABLE II. *Downlink OFDM Modulation Parameters*

Transmission BW		1.25 MHz	2.5 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sub-frame duration		0.5 ms					
Sub-carrier spacing		15 kHz					
Sampling frequency		1.92 MHz (1/2 x 3.84 MHz)	3.84 MHz	7.68 MHz (2 x 3.84 MHz)	15.36 MHz (4 x 3.84 MHz)	23.04 MHz (6 x 3.84 MHz)	30.72 MHz (8 x 3.84 MHz)
FFT size		128	256	512	1024	1536	2048
OFDM sym per slot (short/long CP)		7/6					
CP length (usec/ samples)	**Short**	(4.69/9) x 6, 5.21/10) x 1	(4.69/18) x 6, (5.21/20) x 1	(4.69/36) x 6, (5.21/40) x 1	(4.69/72) x 6, (5.21/80) x 1	(4.69/108) x 6, (5.21/120) x 1	(4.69/144) x 6, (5.21/160) x 1
	Long	(16.67/32)	(16.67/64)	(16.67/ 128)	(16.67/ 256)	(16.67/ 384)	(16.67/ 512)

Depending on the channel delay spread, either short (4.69µs) or long (16.67µs) CP is used.

Supported modulation formats on the downlink data channels are QPSK, 16-QAM and 64-QAM.

Uplink

In the uplink, the LTE uses Single Carrier-Frequency Division Multiple Access (SC-FDMA) as the basic transmission scheme. The principle advantage of SC-FDMA aver conventional OFDM is a lower Peak to Average Power Ratio (PAPR) than would otherwise be possible using OFDM. High PAPR requires expensive and inefficient power amplifiers with high requirements on linearity, which increases the cost of the terminal and drains the battery faster; SC-FDMA solves this problem. Supported modulation formats on the uplink data channels are QPSK, 16QAM and 64QAM.

MBMS

Multimedia Broadcast Multicast Services are performed either in a single cell or multi-cell mode. MBMS-SFN is an elegant application of OFDM for cellular broadcast. Identical transmissions are broadcast from closely coordinated cells simultaneously on a common frequency.

VII. Frequency and Time Synchronization Requirements

Table III shows examples of accuracy for time and frequency. For each system, there are numerous possible configurations which have an impact on synchronization precision to provide. References [3], [4], [5], [6].

TABLE III. *Timing and Frequency Accuracy*

System	TX timing accuracy	Frequency accuracy
GSM	Supported by in band channel	±50ppb (*)
UMTS UTRA FDD	Supported by in band channel	±50ppb (*) for wide area BS ±100ppb for pico/femto
UMTS UTRA TDD	±1.25µs	±50ppb (*) for wide area BS ±100ppb for pico/femto
LTE MBSFN	±1µs	±50ppb (*)
LTE TDD	±1.5µs (**)	±50ppb (*)
DVB-T SFN	±1µs	±1ppb
Mobile WiMAX	±2.5µs or ±1µs for some WiMAX profiles	±8ppm

(*): 16 ppb is often considered as a suitable long term requirement at the input of base station to achieve 50 ppb on the radio interface.
(**): LTE TDD systems may be defined to operate with tens of microseconds phase accuracy by making some

limitations on the deployment and radio frame configuration.

VIII. Other Emerging Applications

In addition to telecommunications, there are various emerging applications that require precision time and frequency -- examples are presented below:

A. Downhole Clocks for Oil and Gas Exploration:

Drilling for natural resources such as oil and gas require precision rugged oscillators that perform at high temperatures, shock and vibration environments. The oscillators are incased in the drilling tool and are generally referred to as sub-surface or downhole clocks. A typical application for the oscillator is to provide the capability for accurately recording downhole seismic measurements. The system normally consists of a surface clock/calibrator that derives its time via GPS and a sub-surface clock as shown in Figure 1.

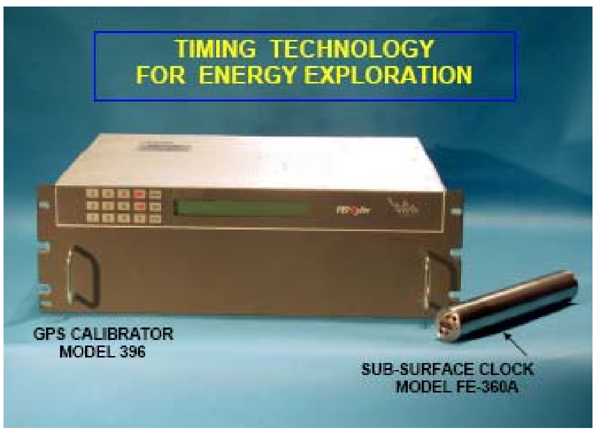

Figure 1. Precision time and frequency system in drilling for oil and gas

In certain seismic applications (often referred to as Vertical Seismic Profiling) the downhole clock is firstly calibrated at the surface then it is lowered into the hole and drilling commences. At the instant that the downhole clock is disconnected from the calibrator it will be in a "free-running" mode. After a certain number of hours or days a seismic event such as an explosion, or a firing of a compressed air gun, sets off acoustic waves on the surface. The explosion is synchronized to the surface clock/calibrator and as shock waves from the explosion travel into the Earth, the downhole sensors such as geophones, and data recording systems that are synchronized to the downhole free-running clock will receive the signals, time tag them and process. In essence, stratifications produce different time delays and geologists analyzing the data can determine the composition of the geological strata. In a typical application, the drill bit sitting at the end of the tool containing the clock, may drill down up to ~5km deep then makes a turn and drills horizontally (or even in upward direction) for additional several kilometers. Upon return to the surface the down-hole clock's time is compared, via calibrator, with the GPS time to validate the data collected down-hole.

The environment that the downhole oscillator experiences is very challenging, but FEI has been very successful in designing and manufacturing downhole clocks. The technology is based on a break-through in two main areas:

a) Optimization of the cut and mounting of the crystal blank to operate in high temperatures and high shock and vibration environments

b) Optimization of the oscillator circuits and ovens

The above technology has rendered robust and reliable clocks that exhibit the following performance characteristics:

- Frequency stability: +/-1E-10 for any combination of temperatures (-20 to +150C), vibrations (up to 20G RMS) and clock orientations in Earth's gravitational field.
- Time accuracy of less than 1ms for a 10 to 14 day down-hole mission.
- Low power consumption of less than 3W at -20C.
- Small size: Ø=1.4" x L=8.0".

Near future applications will require clocks to operate from -20 to 200C.

B. Unmanned Air Vehicles (UAV,) Helicopters, Fixed Wing Aircraft and Military Track Vehicles:

UAV, helicopters, jet fighters and military track vehicles often carry sophisticated radar, weapon guidance systems, communication devices and other sensors that rely on the performance of the internal oscillators that serve as low-noise sources of very stable frequency signals. The internal oscillator may be a stand alone quartz oscillator or an integrated assembly consisting of a rubidium vapor atomic oscillator phased locked to a quartz oscillator. The vibration environment that exists on the above cited platforms is very severe and it causes the oscillators to produce vibration induced spurious sidebands and degradation of phase noise.

FEI has developed a "g" (acceleration) compensated technology that has greatly increased the performance of quartz crystal oscillators in challenging environments. The g-compensation technology has been deployed in a host of systems and is providing performance improvements for critical military platforms in high dynamic environments. The technology is based on a break-through in two main areas:

- New methods of stress-compensated quartz resonator design and manufacturing, which provides for minimum cross-coupling.
- New sensing devices that can more easily be matched and mounted to each resonator axis.

The utilization of the above technologies has resulted in frequency generating systems that greatly improve performance of oscillators in vibrating environment. For example, the phase noise performance of a 10 MHz ovenized oscillator utilized in an airborne application that embodies the technology described above is shown in Figure 2. The improvement varies from approximately 45 dB at 10 Hz to 20 dB at 200 Hz. The electronic g-compensation has, in essence, converted a quartz crystal resonator with a measured g sensitivity of 1E-9/g to one that exhibits an "effective" g-sensitivity of 6.3E-12/g (at 10 Hz), and 4.0E-11/g (at 200 Hz), as illustrated in the lower section of Figure 2.

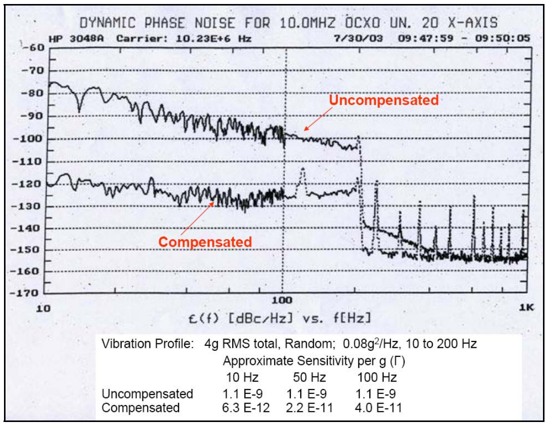

Figure 2. Dynamic phase noise of a 10 MHz hard mounted oscillator

Emerging applications are demanding time errors that are less than 500ns in 24 hours holdover during severe temperature changes. FEI has developed a microprocessor-controlled precise frequency generating system comprised of a rubidium oscillator phased locked to a low g-sensitivity quartz oscillator. The main characteristics of the system consist of:

- High stability Rubidium atomic reference
- Learning to correct for frequency drift
- Temperature compensation

C. Earth Stations:

Emerging applications for g-compensated, stable frequency sources are in Earth Stations as explained by Ernst, et al [12].

The gateway rely on signal sources to provide a stable frequency reference signal for the network. The source is used to synthesize microwave transmit and receive signals locally for gateway signal processing purposes and to serve as a reference for the remotely located signal sources in the network. Achieving extremely low phase noise for this common reference source in order to meet the performance demands over microwave radio links is the challenge. The high phase noise multiplication factor associated with this process drives the phase noise performance of the reference source to be state of the art.

In some applications, the racks are located on elevated flooring in order to facilitate inter-rack connectivity and site thermal management. This physical approach, however, does not provide a vibration-free environment for sensitive phase and frequency signal sources.

The solution implemented to overcome the vibrations caused by the environment is an FEI g-compensated quartz oscillator.

The achieved phase noise performance is demonstrated in Figure 3 below

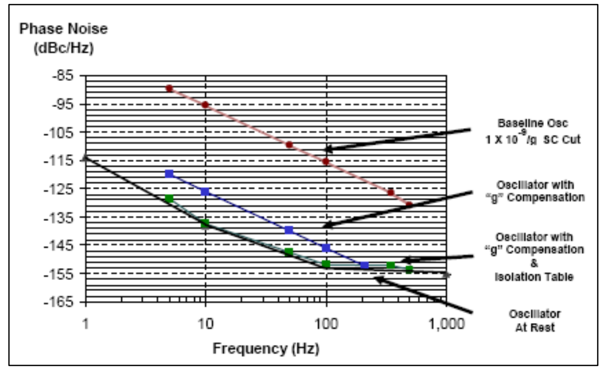

Figure 3. Phase noise performance

IX. GPS AND IEEE 1588

GSM base stations have traditionally derived their long-term frequency accuracy from low performance quartz oscillator embedded in the base station to a recovered clock signal from E1 line backhaul facility. Now, transport networks are rapidly evolving to IP topologies. This technology offers mobile operators the increased backhaul capacity for deployment of high bandwidth data services and also the cost advantage of IP transport. However, the move to Ethernet backhaul eliminates the possibility to recover the synchronisation from E1 line backhaul facility. Moreover we notice that current applications require greater and greater time accuracy. There are two solutions to solve these problems: either to get back time and frequency from the IP network or to generate locally the synchronisation signal from a GNSS system.

For remote base stations, a reliable alternative to backhaul timing references is to employ GNSS-based receivers. GNSS provides a highly accurate and precise primary reference source on the order of 1E-12 (one-day average). GNSS provides also a PPS with a time accuracy of 25ns RMS or better. For example Figure 4 shows a GPS receiver, the PicoSync from FEI.

Figure 3. The PicoSync receiver

The problem with GNSS receiver is that the installation and antenna placement to assure a view of the sky can be sometimes difficult.

Many providers are now considering using IEEE 1588 PTP in new base station deployments to reduce installation costs. To support IEEE1588, all base stations would have a client that would calibrate itself to the master clock using a two-way protocol. Figure 5 shows an example of such a client: the slave clock G1406 from FEI.

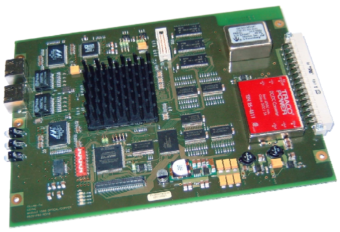

Figure 4. IEEE1588 slave clock

In the two cases, GNSS or IP based protocols are used to control a high precision oscillator located in the GNSS receiver or the 1588 slave. The choice of the oscillator stability and the design of the locked loops are the most important parameters to provide not only a good stability in normal conditions but also in abnormal conditions for example in holdover. Concerning oscillators, FEI can provide OCXO, high precision OCXO and rubidium vapor atomic oscillator.

X. XTAL OSCILLATOR

Precision ovenized-crystal oscillators (OCXO) are typically defined as those oscillators with frequency stability of better than 1x 10-10 over a wide range of environmental conditions. These conditions include operating temperature, humidity, supply voltage variations, repeatability, frequency settability, and frequency drift over long periods of time. Table IV compares the oscillator different technologies.

TABLE IV. *Comparison of oscillator different technologies*

Oscillator Type	Frequency Stability (–40°C to +75°C, and high slew rates)
Crystal Oscillator (XO)	$1x10^{-4}$ to $1x10^{-5}$
Temperature Compensated Crystal Oscillators (TCXO)	$1x10^{-6}$
Microcomputer Compensated Crystal Oscillators (MCXO)	$1x10^{-7}$ to $2x10^{-8}$
Oven Controlled Crystal Oscillators (OCXO)	**$1x10^{-8}$ to $3x10^{-10}$**
FE-405A Series High-Precision Double Oven Crystal Oscillator (OCXO)	**$1x10^{-10}$**
Rubidium Atomic Frequency Standards (Rb) (–10°C to +70°C)	$3x10^{-10}$ to $7x10^{-11}$
Cesium Atomic Standard (Cs) (0°C to +50°C)	$1x10^{-11}$ to $1x10^{-12}$

As far as the Quartz oscillators are concerned, FEI proposes OCXO and high precision OCXO. This last type of oscillator approaches the stability of Rb devices, but at a third of the atomic frequency source's price. For example, Figure 6 shows the FEI FE-205A, a family of high precision OCXO.

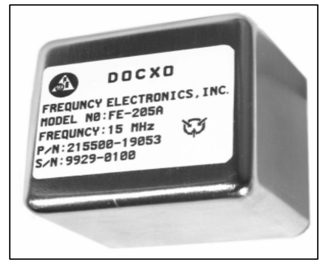

Figure 5. FE-205A

The characteristics of this oscillator are resumed hereunder:

- Producible in large quantities
- Excellent temperature stability < $1x10^{-10}$ per 50°C
- Low aging: typically < $1 x 10^{-11}$ / day; < $20 x 10^{-9}$/10 year
- Near-Rubidium accuracy at 1/3 the cost
- Any frequency from 1 pps to 100 MHz
- Analog or digital frequency control with better than 1% linearity
- Standard frequency: 10 MHz and 15 MHz

These products are capable of operating in extreme temperature swings and are applicable for cellular base stations, stratum clocks, GPS timing systems, IEEE1588 slave clocks, test equipment, aviation, instrumentation and military.

XI. RUBIDIUM OSCILLATOR

Rubidium atomic frequency standards are being used increasingly in telecommunication applications, particularly wireless telephony networks. The possibility of frequency stability sufficient to eliminate the need for scheduled re-calibrations, along with small size, low power requirements, wide temperature range operation, and low cost make these devices attractive candidates for telecommunication applications.

For example, Figure 7 shows the FE-5680A Rb frequency standard is 3.5 x 5 x 1 inches, a design suited to PC board slot mounted applications.

Figure 6. FE-5680A

Many commercial applications for precision frequency standards demand performance over an extended temperature range. Often frequency variation with temperature is the performance-limiting feature of these devices.

The FE-5680A operates at any temperature between -10 and +60°C, a temperature range required for indoor rack-mounted telecommunication hardware with limited air flow.

Performance characteristics for this RB frequency standard are shown in Table V.

TABLE V. *General Performance*

	FE-5680A
Frequency :	Fac. Settable 1 Hz to 20 MHz
Phase Noise :	10 Hz. -100 dBC
	100 Hz. -125 dBC
	1000 Hz. -145 dBC
Temp Range :	- 10°C to + 60°C
Freq vs Temp:	$\pm 3 \times 10^{-10}$ over range (standard)
	$\pm 5 \times 10^{-11}$ over range (option)
Stability :	
Allan Variance :	1.4 x 10-11/√t (standard)
	$5.0 \times 10^{-12}/\sqrt{}_t$ (option)
Drift :	2×10^{-11}/day (standard)
	2×10^{-12}/day (option)
	2×10^{-9}/year (standard)
	2×10^{-10}/year (option)
Retrace :	5 x 10-11

This product can be integrated in a GPS receiver for example. The precision in frequency (10 MHz) and in time (PPS) of the whole will be highly superior to the required precisions in telecommunications. It's possible to have errors less than 1 µs in 24 hours holdover in normal situation.

XII. CONCLUSION

New transmission technologies require time and frequency accuracies more and more important.

These accuracies can be reached by means of GPS receivers or IEEE 1588 V2 equipments. The basic element of these systems is a quartz or rubidium oscillator which ensures synchronization quality and stability in holdover. These products are capable of operating in extreme temperature swings.

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