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# An Evaluation of Dependencies of Critical Infrastructure Timing Systems on the Global Positioning System (GPS)

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Stocks were traded in the United States for about 200 years, beginning in the 1790s, before it finally became necessary to implement and regulate time synchronization requirements. The main reason that time synchronization finally became a concern was the widespread usage of electronic trading platforms and automated stock exchanges that began in the late 1990s. Electronic trading fundamentally changed stock exchanges; soon most market makers were no longer individuals working the telephones or physically waiting in line to place orders. Instead, computers began to automatically execute trades, and to buy and sell stocks to each other, based on software algorithms. These automated trading platforms greatly reduced the amount of time needed to execute a transaction making the markets move faster. In addition, automation led to smaller spreads, resulting in the decimalization of stock prices which began on the NYSE and NASDAQ in 2001. Prior to decimalization, stock prices were listed in fractional dollars, which kept the spread large; for example, if a stock traded in price increments of 1/8 of a dollar the spread would be at least 12.5 cents, but decimalization reduced the minimum price increment to one cent [72]. Smaller spreads made the market more liquid but created the incentive for market makers, now dealing with reduced profits from tighter spreads, to execute more trades [73].

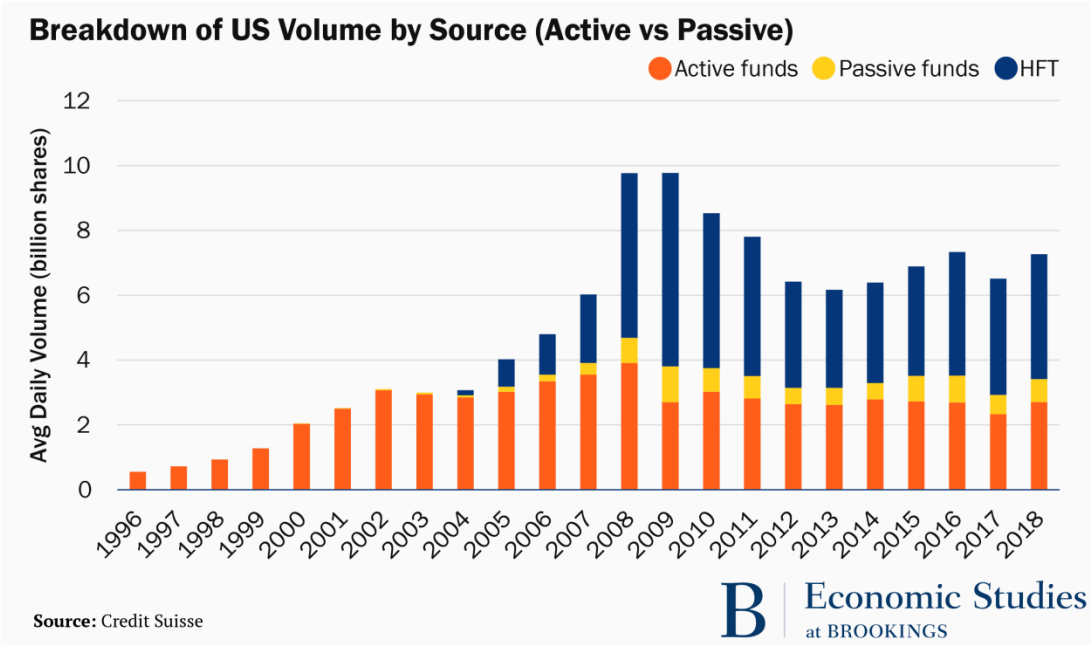


**Fig. 15**. U. S. stock volume from 1996 to 2018, and the contribution of high frequency trading (HFT).

Each of these factors led to the now widespread practice of high frequency trading (HFT) where a much larger number of transactions could occur in a given time period than before, because the trades executed by automated trading platforms can execute in intervals measured in microseconds [74]. At least half of the transactions in today's stock markets are the result of HFT. Figure 15 [75] shows the average trading volume, or the number of shares of stock traded per day, for U. S. stock exchanges from 1996 to 2018. Note that less than one billion shares per day were traded before electronic trading platforms began operation in the late 1990s. This number increased to nearly 10 billion shares per day in 2008 and 2009. Note also that HFT did not have a significant impact on trading volume until 2004, but since 2008 has accounted for at least half of the total volume. Finally, it is interesting to note that stock market volume has leveled off in recent years and remained about 6 billion and 7.5 billion shares per day each year from 2012 to 2018. Even so that is more than 10× the daily volume of the markets before the use of electronic trading platforms.

The practice of HFT made it essential for all stock exchanges and trading platforms to be able to document that their time stamps are accurate, to avoid stock market fraud and manipulation. To illustrate the importance of accurate time stamps, consider a hypothetical situation where a retail investor, trading from a home computer, is preparing to submit an order for 100 shares of ACME Corporation stock. Before submitting the order, the investor checks the display of their online trading software and notes that the current bid is $9.23, and the current ask is $9.25. The display also indicates that no one else is in line to buy the stock. Thus, they understandably assume that the ask price, $9.25 per share, is the price they will pay and "click" to submit the order. A fraction of a second later a large investor (such as a hedge fund or investment bank), submits an order to buy 1,000,000 shares of ACME. This large order arrives at the stock exchange after the small order, but the exchange, for reasons unknown to the retail investor, fraudulently elects to execute the large trade first. The large trade immediately raises both the bid and the ask price by 15 cents, to $9.38 and $9.40, respectively. This action causes the retail investor to instantly lose money, regardless of whether they entered a market or limit order. If they entered a market order, meaning that they agreed to accept the current ask price regardless of what it is, they'll pay $9.40 for the stock they were expecting to buy at $9.25. If they entered a limit order, indicating that $9.25 was the most they will pay, they missed out on the trade completely because the large investor was allowed to buy their shares and their order was never filled. Meanwhile, the large investor who "cut ahead in line" has the option of selling at least some of the shares they just purchased at the new bid price, taking an instant profit [71].

Cutting in line is called "front running" and is illegal, but when computers are making the trades, it is essentially impossible to prove or regulate without accurate time stamps. It only becomes possible if distributed trading platforms rely entirely on clocks that are synchronized to a common reference clock. In addition, the resolution of the time stamps used to record each transaction must be finer than the execution times of the trade. For example, if trades are being stamped with a resolution of one second, it means that the time stamp can display 12:22:01 (12 h, 22 min, and 1 s) and 12:22:02, but nothing in between. Thus, a time stamp of 12:22:01.5 cannot be recorded. This is unacceptable with HFT, because a stock exchange can potentially execute many thousands of trades within a one second interval and each of those trades would have the same time stamp. This makes it possible for the market maker to reorder them in any way that suits their purposes, because there will be no way for an auditor reviewing the transaction logs to prove which orders arrived first [71]. Concern by regulators in the 1990s that trades were not always being executed in the best interest of customers led to the establishment of order audit trail systems (OATS) and the first rules for the synchronization of stock market clocks, as described in the next section.

### IV.B Time Synchronization Requirements of Stock Exchanges

Prior to the advent of distributed electronic trading platforms and HFT, many of the clocks maintained by stock exchanges were mechanical devices that physically stamped the time, in ink, onto the paper documents used to record transactions. These clocks were not always synchronized and seldom had the ability to display seconds. This changed in August 1996, when the U.S. Securities and Exchange Commission (SEC) issued a report [76] that included findings from an investigation of the practices of the National Association of Securities Dealers (NASD) and the NASDAQ. The report alleged that the NASD and NASDAQ did not always act in the best interest of customers — some trades were improperly executed, and some collusion existed among market makers. A financial settlement was reached between the SEC and NASD that also included new regulations; the NASD was required to improve market surveillance and to develop an enhanced Order Audit Trail System (OATS). To new OATS rules went into effect in August 1998. One of the rules, rule number 6953, was entitled "Synchronization of Member Business Clocks" [77] and represented the first stock exchange synchronization requirement. It required computer systems and mechanical clocks to be synchronized every business day before the stock market opened to ensure that time stamps were accurate. The synchronization requirements were as follows:

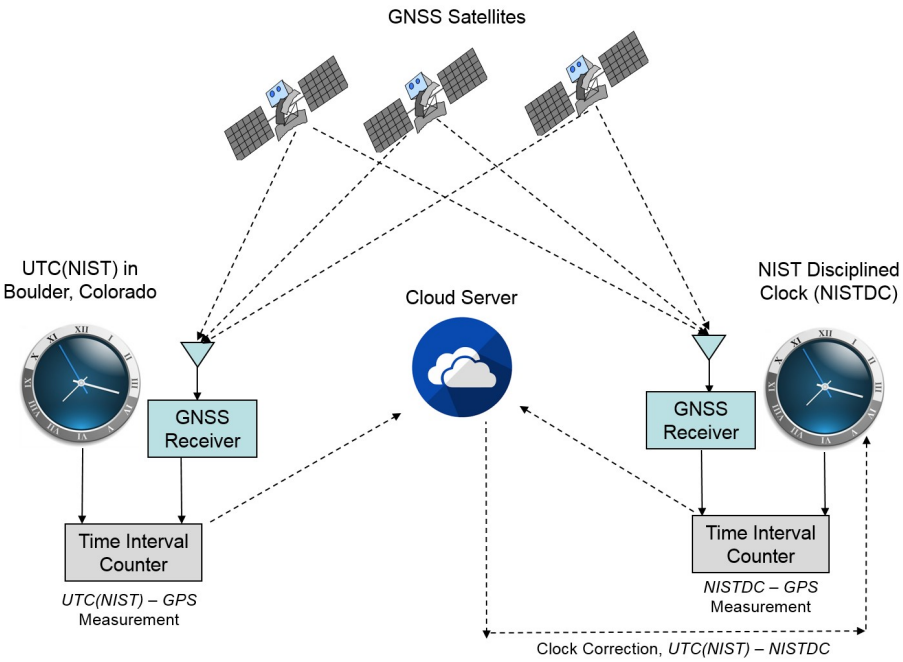


**Fig. 17.** NISTDC common-view link to UTC(NIST).

Common-view observations routinely show that a locked NISTDC seldom deviates by more than ±10 ns (±0.01 µs) from UTC(NIST) and that its average time offset is near 0. To illustrate this, Fig. 18 shows a 6-month (July to December 2019) comparison of a NISTDC, located at a major US stock exchange, to UTC(NIST). The peak-to-peak variation over the 6-month interval is ~25 ns, but most data points fall within ±5 ns and the average time offset is less than 0.1 ns, or essentially 0.

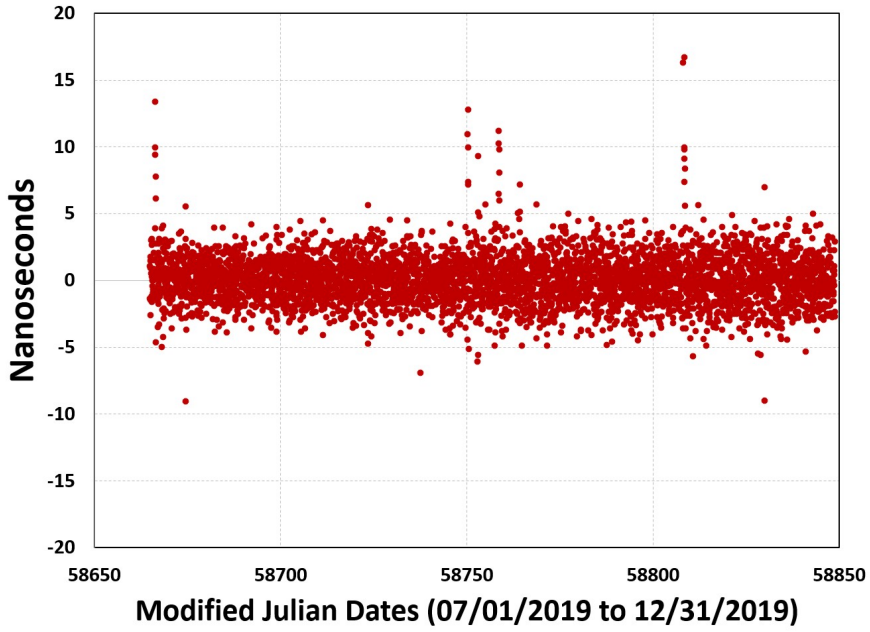


**Fig. 18.** Accuracy of NISTDC operated by a major U. S. stock exchange, with respect to UTC(NIST).

Time servers located in the same data center as a NISTDC can eliminate the need for connection to a GPS antenna, by using 1 pps signals distributed from the NISTDC via coaxial cable as their synchronization source and by obtaining time-of-day information from the NISTDC's integrated NTP/PTP server. However, regardless of whether a time server is synchronized with UTC(NIST) or GPS, it can still be monitored by the NISTDC, which can simulate a client computer and send time requests to servers every 10 seconds. It then compares the time stamps in the received packets to the time kept by the NISTDC, a comparison made with 0.1 µs resolution. When the NISTDC resides on the same local area network (LAN) as the time server, the measured time offset of a properly synchronized server typically ranges from a few microseconds to about 50 µs when compared to the NISTDC. Figure 19 shows the time offset of an NTP server, operated by a major US stock exchange, when compared to UTC(NIST) during the last 100 days of 2019 (one data point per hour). The average time offset of the NTP server clock is 20 µs and its time deviation (stability) is < 1 µs at an averaging period of 1 day.

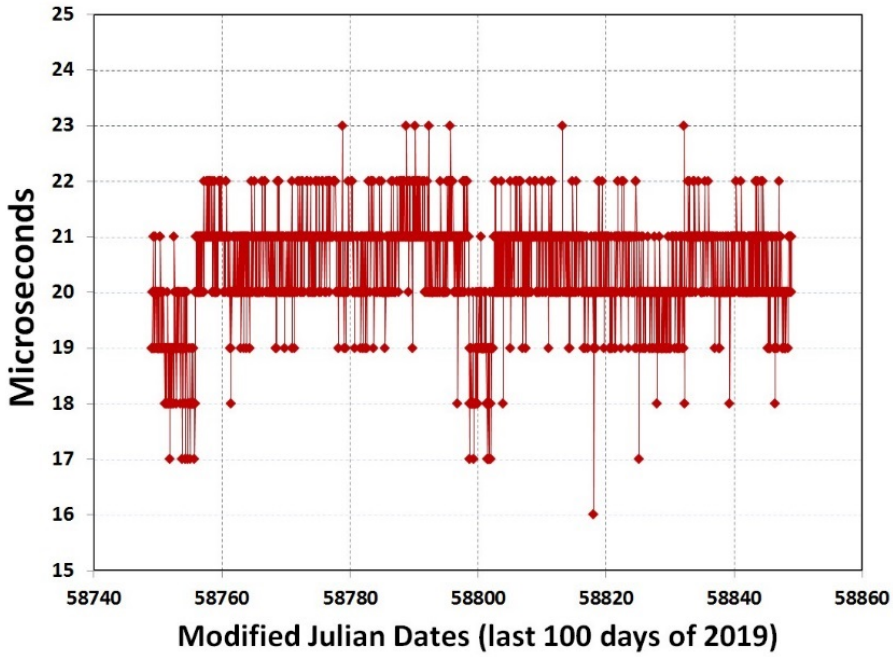


**Fig. 19.** Accuracy of an NTP time server at a major US stock exchange, with respect to UTC(NIST).

NISTDC units synchronize some of the world's largest stock exchanges and are installed at data centers near New York City and Chicago in the U. S., as well as in London and Frankfurt in the European Union, and in Tokyo, Japan. Stock exchange clients who utilize the NISTDC have full 24/7 access to their clock data via a web portal. Other nations have designed systems to deliver time to stock exchanges and for monitoring and verifying clocks, including the National Physical Laboratory (NPL) in the United Kingdom, which utilizes dedicated fiber and transfers time via the loop-back method with PTP or the two-way method with White Rabbit [87], and the National Research Center in Canada, which utilizes a common-view disciplined clock method similar to the NISTDC [88].

The third and final question is, what will happen to stock exchanges if GPS is unavailable? A GPS failure would, of course, cause synchronization to be lost after a period commensurate with the holdover capability of the stock exchange clocks, if no other backup timing systems were available. This failure could be widespread, as GPSDCs are commonly found in stock exchange data centers. However, the loss of synchronization, unless it involved some extreme and unusual situations, such as clocks being targeted, spoofed, and falsely set by U. S. adversaries, would probably not cause the stock exchanges to stop trading

or cause markets to crash. Unlike some telecommunication systems (Section VI), which for technical reasons require synchronization requirements to be met to keep networks operational, the synchronization requirements of stock exchanges are regulatory requirements that were put in place to help protect investors. Thus, rather than resulting in a catastrophic incident that dominates the headlines; a synchronization outage would likely have the more subtle effect of simply providing less protection to investors against fraud and market manipulation, a situation which might be invisible and not known to those who incur monetary losses.

## V. Timing Requirements and Dependencies of the North American Power Grid

The combined electric power transmission and distribution system in the U. S. is commonly known as the power grid or simply the "grid". The grid is the most critical of our critical infrastructure systems, as it supplies the electricity that powers all other sectors. The grid is the backbone of our economic sector and essential to national safety and security, thus overestimating the importance of the grid as it applies to our quality of life in the United States is nearly impossible.

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid [89]. The grid that NERC oversees consists of four distinct interconnections, shown in Fig. 20, that supply power to the U. S. and Canada at a nominal frequency of 60 Hz. The two major interconnections are the Western, which supplies power to more than 80 million people in all or part of 14 western states and two Canadian provinces [90], and the Eastern, which supplies power than more than 200 million people (~68% of the U. S. population), in all or part of 36 states [91]. Most of the state of Texas is covered by the Electric Reliability Council of Texas (ERCOT) interconnection, and a fourth interconnection covers the Canadian province of Quebec. The grid systems in Alaska and Hawaii are not connected to the power system shown in Fig. 19, but the coordinating body in Alaska is an affiliate of NERC. All told, the U. S. power grid consists of more than 360,000 miles (~580,000 km) of transmission lines, including approximately 180,000 miles (~290,000 km) of high-voltage lines, connecting to about 7,000 power plants [92].

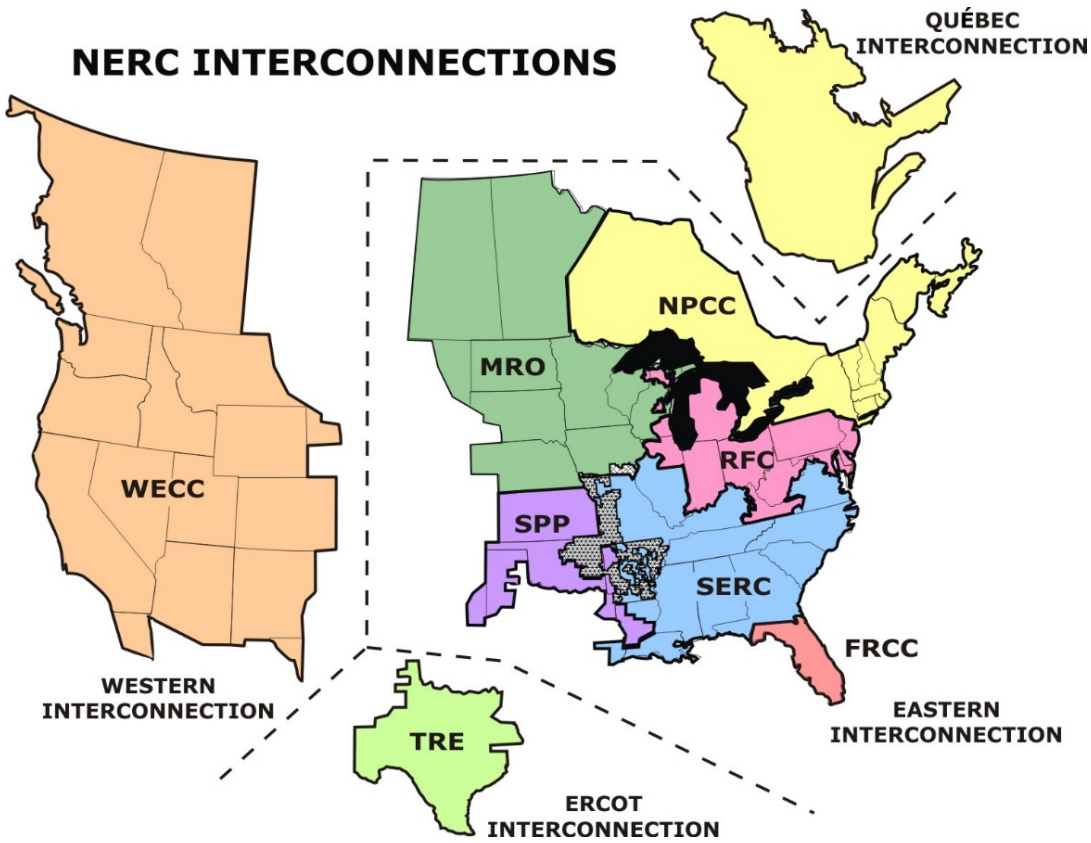


**Fig. 20**. Regions and interconnections in the North American power grid.

## V.A The Importance of Time Synchronization to the Power Grid

Because the power grid encompasses many large and geographically separated systems that need to be synchronized, it requires access to a UTC reference clock that is easily accessible across a wide area. Time synchronization is needed for a variety of applications, including: continuous monitoring of the state of the power grid and its operating limits, protecting grid assets by quickly identifying and locating grid failures so they can be repaired before wide spread outages occur, and recently, as synchronization capability has continued to improve; advancing the grid's real-time measurement and control capabilities in ways that make better use of the grid's resources, so the needs of a growing population can continue to be met.

Locating faults on a transmission line is the application identified by power companies as having the most stringent synchronization requirements [93]. A fault on a transmission line can occur due to switching operations, a lightning strike, or other causes, and numerous methods of fault detection exist [94]. One method, known as travelling wave fault detection, is based on the principle that a traveling wave is generated at the point of a line termination or fault. Normally, the voltage and current waves travelling on a transmission line are related by the surge impedance of the line, but when a fault occurs, voltage collapses, tending towards 0, while the current wave doubles. This creates a high-frequency pulse that travels down the transmission line at nearly the speed of light. The arrival time of this pulse is measured at both ends of the line and time stamped by clocks that are synchronized to each other and that usually have a resolution of 0.1 µs [95]. This method became effective with the use of GPSDCs, which made it possible to identify the tower nearest to where a fault occurred. For example, if the transmission line is supported by high voltage towers that are spaced 300 m apart, locating the fault requires at least 1 µs synchronization, or the period of a 300 m wavelength [96].

Another synchronization requirement involves disturbance monitoring equipment (DME), which includes protective relays, sequence of event recorders, and digital fault recorders (DFRs). Relays are the workhorse devices used to protect grid assets; they measure the time interval between a triggering event such as a fault and respond quickly, for example by tripping a breaker, opening a line, or isolating a power plant, before significant damage occurs [96]. Time synchronization is normally provided by either GPS, or through a PTP device which is usually synchronized internally with a GPSDC and that may also distribute time via an IRIG time code [97]. Sequence of event recorders are used to record exactly when an incident, such as a breaker trip, occurs. They help answer questions about chronological relationships, allowing investigation of issues such as lightning strikes and downed poles. The current and voltage on the grid is typically monitored and sampled at high rates with DFRs, which time stamp data that is aligned with data from other recorders to help correlate and analyze power grid events. For example, the time stamped voltage and current data can be used to find the point of origin of a lightning strike. The NERC synchronization requirement for DME is ±2 ms with respect to UTC [98]. This also applies to the data recorded for post-mortem failure analysis [99]. However, in many cases utility companies rely upon and demand much tighter synchronization and categorize DME equipment based on guidelines presented in the International Technical Commission (IEC) 61850 series of standards, where the accuracy requirements for the time stamping of events are summarized in five time performance classes, T1 to T5, that range from 1 ms to 1 µs [100, 101].

Most of the attention in power grid synchronization, however, relates to phasor measurement units (PMUs), the instruments that perform synchrophasor measurements. A phasor is a phase vector that represents a sine wave, in this case the 60 Hz alternating current (AC) sine wave generated by the power grid. A complete sine wave can be constructed by a single vector that rotates counter clockwise in a circle. This relationship works because a sine wave is a projection of a rotating circle's radius. A phasor rotates at an angular velocity ($\omega$), expressed in radians per second, of $\omega = 2\pi f$, where $f$ is the frequency of the waveform. In this case, $f$ is the grid frequency, or 60 Hz.

In the power industry, however, the term phasor normally refers not to a rotating phasor, but rather to a stationary phasor, recorded at a given point in time, that indicates the amplitude and direction of the sine wave. Figure 21 is a simplified diagram where the red vectors inside the circle are stationary phasors, or "snapshots" of the sine wave at a given time. The blue lines connect the stationary phasor to the corresponding point on the sine wave.

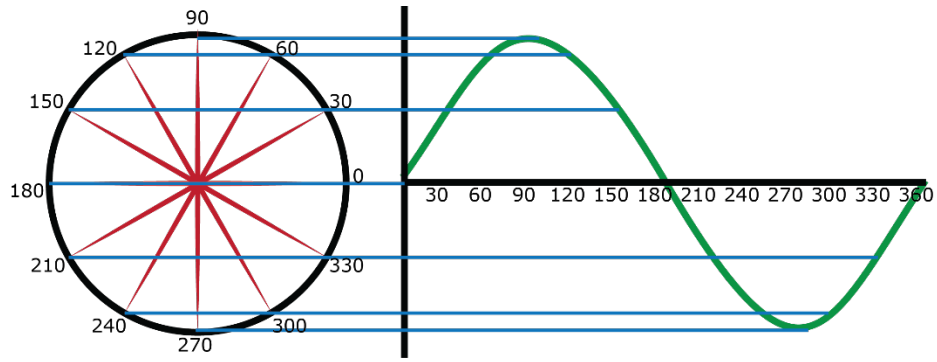


**Fig. 21**. The relationship between a phasor and a sine wave.

Synchronized phasors, or synchrophasors, are referenced to an absolute point in time by using UTC as a common clock, distributed by a GPSDC. Figure 22 shows the phase of a sine wave sampled at two points, $\delta_0$ and $\delta_1$, with $\Delta\delta$ the phase angle difference between the two samples, as represented by the two stationary phasors inside the circle, and $\Delta t$ is 1 / sampling rate. The frequency, $f$, can be derived as $f = f_{nom} + \Delta f$, where $\Delta f = \Delta\delta / (360^{o} \times \Delta t)$.

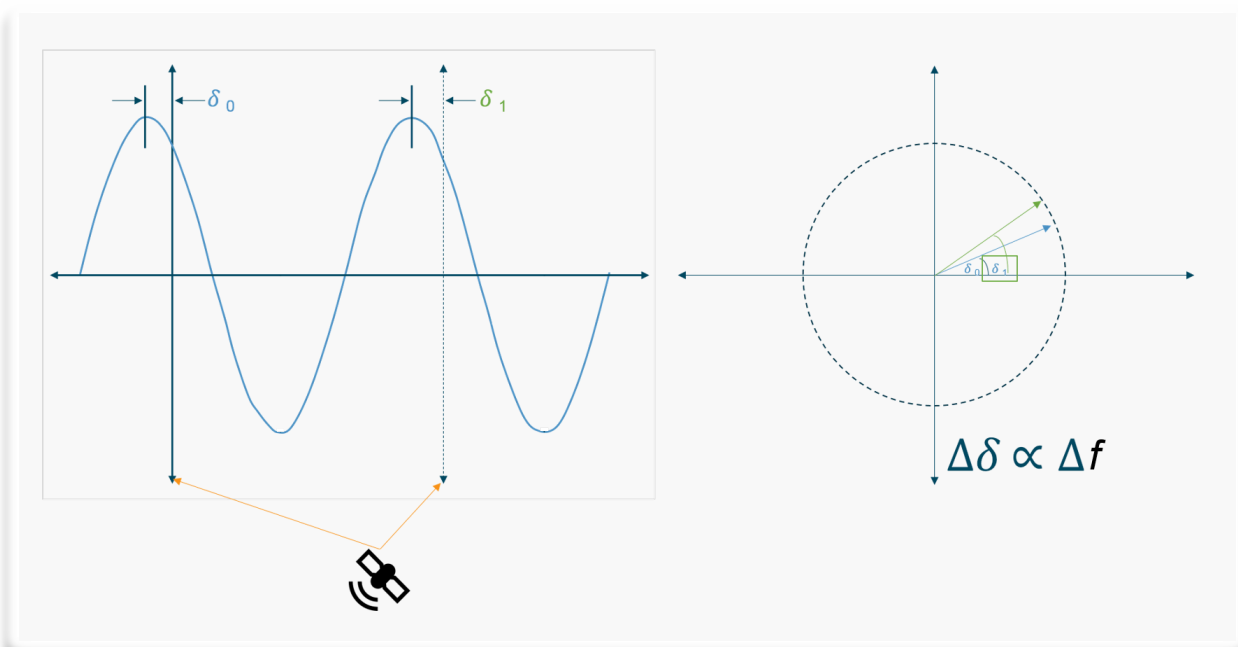


**Fig. 22**. A synchrophasor measurement.

A PMU measures the total vector error (TVE), which is the difference between a measured phasor and a true or ideal phasor, with no measurement uncertainty. The word "total" is used because the TVE includes all error sources, including phasor angle and phasor magnitude, in addition to the time synchronization error. The TVE is expressed as a percentage, and the acceptable PMU tolerance for a TVE measurement is 1%, as stated in the *IEEE C37.118.1* standard. A 1% TVE can be visualized as a circle drawn on the end of the phasor, as shown in Fig. 23, with the size of the circle exaggerated for clarity. The error reaches 1% even when the error in amplitude is zero, if the error in angle reaches 0.573º. PMUs are calibrated by generating a test signal of known accuracy and meet specifications if the samples they collect do not lie outside the circle [102].

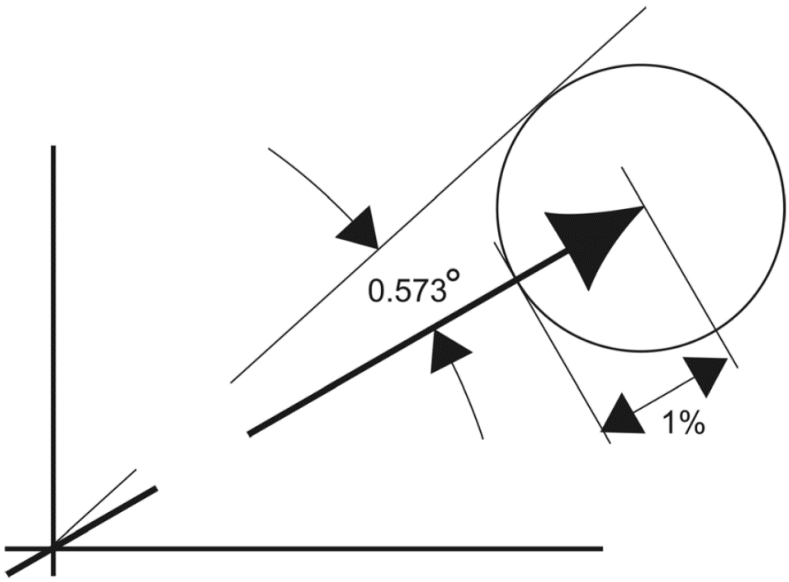


**Fig. 23**. A total vector error (TVE) of 1%.

Because the period of a 60 Hz sine wave is 16 666 µs, an error in phase angle of 0.573º will occur if the time synchronization error exceeds 26.5 µs (period / (360 / 0.573)). However, because Section 4.3 of the *IEEE C37.118.1* standard states that a time source "at least 10 times better than these values corresponding to 1% TVE is highly recommended", the requirement is usually considered to be 2.6 µs or less, with the desired accuracy stated as 1 µs, which corresponds to a 0.022º error in phase angle. Section 4.3 of the standard states that the resolution should be commensurate with this level of accuracy, by asserting that the "time tag shall accurately resolve time of measurement to at least 1 µs within a specified 100 year period." Section 4.3 also mentions traceability to UTC in three places, beginning with the clause stating that "the PMU shall be capable of receiving time from a reliable and accurate source, such as the Global Positioning System (GPS), that can provide time traceable to UTC ...." [102].

A PMU performs synchrophasor measurements and records time stamped voltage and current vector values that are sent very quickly to an operating center, typically at a rate of 30 to 120 samples per second. Data from multiple PMUs are sent to a centralized phasor data concentrator (PDC) where the readings are aligned and compared to provide a near real-time indication of the health of the power grid. This data can be used to make real-time decisions about power allocations within the grid. GPS was an enabling technology for synchrophasor measurements. Although the concept of a PMU had been explored long before the GPS satellites were launched, GPS was necessary to provide the necessary timing accuracy. The first prototype PMU was assembled by Phadke and his colleagues at Virginia Tech in 1988 with a GPS clock [103], and commercial units soon followed. As of May 2017, about 1,800 PMUs were in use in North America, as shown in the map (Fig. 24) provided by the North American SynchroPhasor Initiative (NASPI).

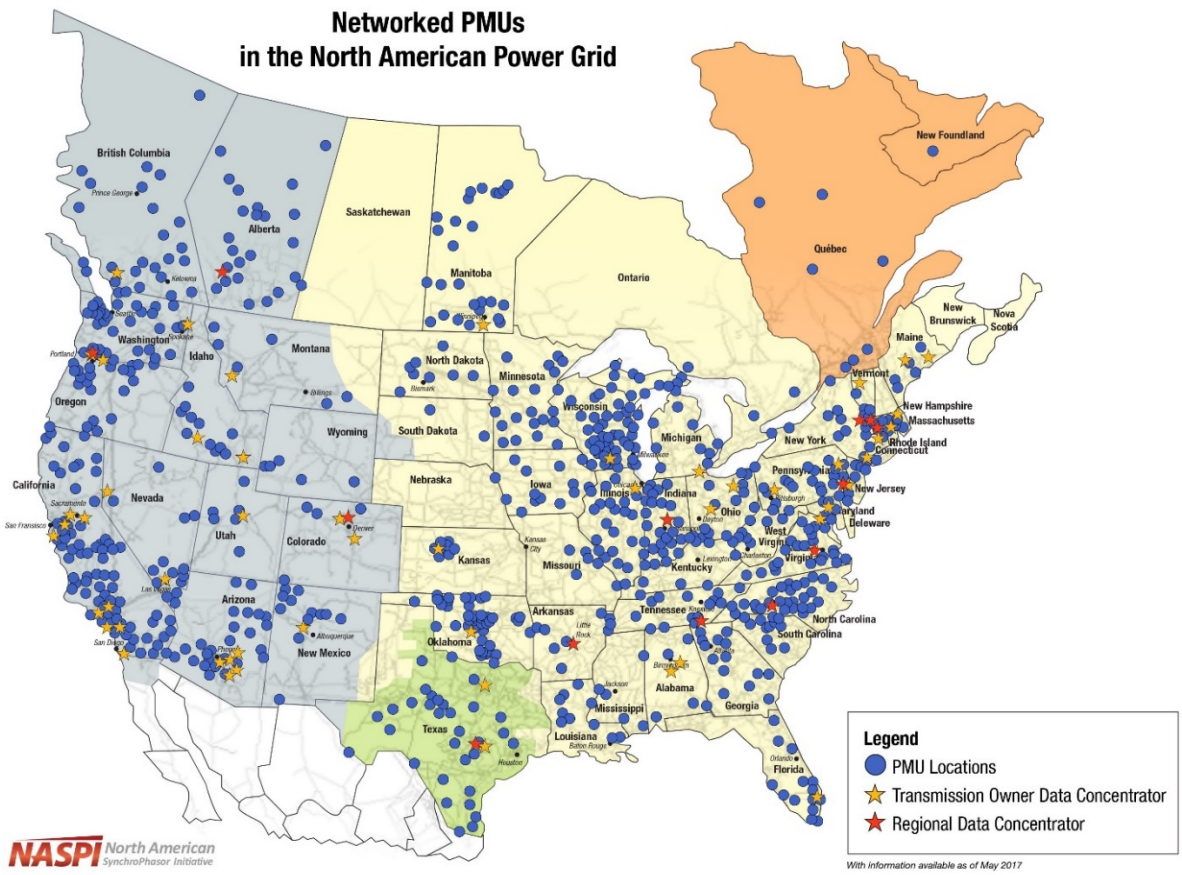


**Fig. 24**. Map of PMUs in the North American power grid as of May 2017.

## V.B Time Synchronization Requirements of the Power Grid

Power grid synchronization requirements are essentially based on speed and response time, the equipment needs to report upon and respond to events quickly enough to prevent wide area failures. Table 6 summarizes the basic synchronization requirements.

**Table 6.** Summary of power grid synchronization requirements.

| Grid application | Synchronization requirements (relative to UTC) |
|---|---|
| **Sequence of events recorder** | 50 µs to 2 ms [95, 98, 99] |
| **Digital fault recorder** | 50 µs to 2 ms [95, 98, 99] |
| **Protective relays** | < 1 ms to 2 ms [95, 98, 99] |
| **Synchrophasor/PMU** | 2.6 µs, 1 µs resolution [102] |
| **Traveling wave fault location** | 100 ns [95] |

Timing requirements for communication systems used by power utilities are often based on PTP and are provided in [100], and general guidelines for designing power substation timing systems are provided in [104].

### V.C GPS Timing Dependencies of the Power Grid

The synchronization requirements of the power industry vary (Table 6), because the entire system has evolved over many years. The older parts of the system have less stringent timing requirements because they were designed using technologies that predated the Global Positioning System (GPS). The newer parts of the system, in particular PMUs, were designed using GPS, and thus are dependent upon GPS – either through direct reception or through a network connection via PTP, to provide them with the necessary accuracy.

The power industry is well aware that bad things can happen when synchronization is lost. An often cited example is the massive blackout that occurred on August 14, 2003 in eight states and two Canadian provinces. The outage lasted for two days in some U. S. areas with rotating blackouts occurring for about two weeks in parts of Canada. Time synchronization was not the root cause of the blackout, but recommendation 12 from the detailed post-mortem report prepared by NERC was to "Install Additional Time-Synchronized Recording Devices as Needed," noting that:

> "*A valuable lesson from the August 14 blackout is the importance of having time-synchronized system data recorders. NERC investigators labored over thousands of data items to synchronize the sequence of events, much like putting together small pieces of a very large puzzle. That process would have been significantly improved and sped up if there had been a sufficient number of synchronized data recording devices.*
>
> *NERC Planning Standard I.F — Disturbance Monitoring does require location of recording devices for disturbance analysis. Often time, recorders are available, but they are not synchronized to a time standard. All digital fault recorders, digital event recorders, and power system disturbance recorders should be time stamped at the point of observation with a precise Global Positioning Satellite (GPS) synchronizing signal. Recording and time-synchronization equipment should be monitored and calibrated to assure accuracy and reliability.*
>
> *Time-synchronized devices, such as phasor measurement units, can also be beneficial for monitoring a wide-area view of power system conditions in real-time, such as demonstrated in WECC with their Wide-Area Monitoring System (WAMS).*" [105]

In today's grid, where GPS clocks and PMUs are widely deployed (Fig. 24) and that, when working normally, have no trouble meeting synchronization requirements, the concern has shifted to the reliability of GPS and the dependence upon one timing source. For example, control applications, both automated or based on analytical decisions made by power grid operators, will be adversely affected if the time stamps from GPS are inaccurate or lost. If the time signal received by a PMU is jammed or spoofed, that error will cause false calculations of phase angle and a misalignment of measured grid conditions relative to other PMUs.

The *IEEE 2030.101* standard addresses timing system vulnerabilities in Section 4.14, noting that the "single best tool" for mitigating vulnerabilities is a high-quality time standard with sufficient holdover to allow "synchronization processes to continue unabated for extended periods of time" when the reference signals are lost. It also recommends installing multiple diverse time references, because it is "unlikely that diverse reference signals will be lost at the same time [104]." However, the signals it recommends, such as PTP, which is likely to be derived from GPS, and WWVB, which is unlikely to have sufficient accuracy, simply reminds us that diverse backup choices are limited.

In conclusion, power grid operators have benefitted tremendously from GPS time synchronization but concerns about GPS reliability have currently dissuaded them from pursuing fully automated operations, which appears to be a wise decision, especially when we consider the consequences of wide area outages. As the NASPI Time Synchronization Task Force stated in 2017:

> "*Power system owners and operators use primarily GPS as the source for timing and determining asset position. Today, GPS disruptions complicate (with higher cost, longer duration, and lower efficiency) but do not kill grid operations. For mission-critical time-synchronized applications in the future, however, GPS and alternate time sources (and the ways they are delivered and used) will need to become more reliable* [95]".

## VI. Timing Requirements and Dependencies of Telecommunication Systems

The word telecommunication is derived from the Greek prefix, *tele*, which means "far off" or "from afar" or "from a distance" and the Latin word, *communicare*, which means to "make something common" or to "share". The field of telecommunications is exceptionally broad, because it includes systems that share information of almost any nature across distances of nearly any length through a transmission medium. The transmission medium can be wired, for example, information sent over wires or cables, or wireless, involving electromagnetic radiation that travels through free space as radio waves or light.

Long established methods of sharing information, including one-way transmission or broadcast systems such as television and AM/FM radio, qualify as telecommunication systems. These systems do have frequency syntonization requirements, albeit modest by modern standards, typically parts in $10^5$ [106]. However, the focus of this section will be on two-way telecommunication systems used by individuals for personal communications and to obtain information. These systems can be classified as critical infrastructure because human life and safety often depend upon them, especially in times of emergency. Mobile phone networks, first demonstrated by Motorola in 1973 [107] but used by relatively few Americans until the 1990s, have become the dominant system of this type. Figure 25, obtained from ITU data [108], graphs the number of mobile phone subscriptions in the U. S. from 2000 to 2018, a number that now exceeds 400 million; or more than one phone for every U. S. resident. The graph also shows how the number of fixed-telephone subscriptions, commonly known as land lines, has declined during this same period, and that mobile phone subscriptions surpassed land line subscriptions in 2004. Today, the ratio of mobile phone to land line subscriptions is about 4:1, indicating that many individuals and businesses now rely exclusively on mobile phones as a communication device. Surveys conducted in June 2019 indicate that about 96% of U. S. residents over the age of 18 have a mobile phone and for about 81% of residents, their mobile phone is a smartphone [109], which means that it provides access to numerous other telecommunication systems in addition to voice telephone calls, including functioning as a mobile Internet platform.

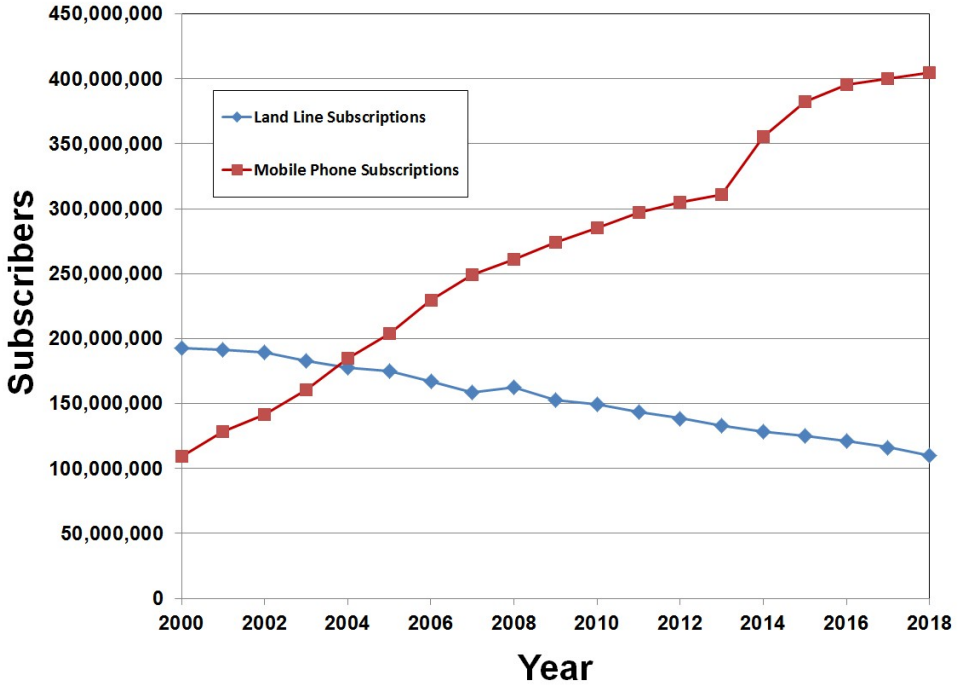


**Fig. 25**. U. S. mobile phone versus land line subscriptions, 2000 to 2018.

## VI.A The Importance of Time Synchronization to Telecommunication Systems

Synchronization in telecommunications networks is the process of aligning the clocks of transmission and switching equipment so that operations occur at the correct time and in the correct order. Synchronization requires the receiver clock to acquire and track timing information in a transmitted signal that originated from another clock. The required level of synchronization/syntonization varies, of course, depending upon the type of network, but all networks will lose data or in some cases fail completely if the basic requirements are not met. More stringent synchronization can help to maximize the use of available bandwidth so that networks can operate at full capacity and make the best use of available resources.

The beginnings of the current high level of importance that synchronization has on telecommunication networks can be roughly traced to the divestiture of AT&T on January 1, 1984 [110]. Prior to this date, all telephone calls in the U. S. were routed through a single telephone company that was handling approximately 600 million calls per day. A very tiny percentage contained data, from data links between computer modems, but for all practical purposes everything carried by the network was voice communications. Synchronization for the entire network was provided by the Bell System Reference Frequency (BSRF), which was located underground in Hillsboro, Missouri. It consisted of three cesium clocks, had a frequency offset of less than $1 \times 10^{-11}$ [110, 111], and, because the system originated prior to GPS, traceability was established to the USNO via a Loran-C link [110].

After the divestiture, AT&T was divided into seven Regional Bell Operating Companies (RBOCs). Each of these companies now had to maintain its own reference clock that had equivalent accuracy to the BSRF. These clocks were called the primary reference source (PRS) by the American National Standards Institute (ANSI) [112], or the primary reference clock (PRC) by the ITU [26]. In order for the various carriers to interconnect and exchange data with each other, each of their clocks had to appear to be synchronized with all of the others, even though no synchronization paths existed between carriers (Fig. 26). This is called plesiochronous operation, which means that the system is almost, but not quite, synchronized. It works with a minimal amount of data loss if each PRS stays within frequency tolerances defined with respect to UTC.

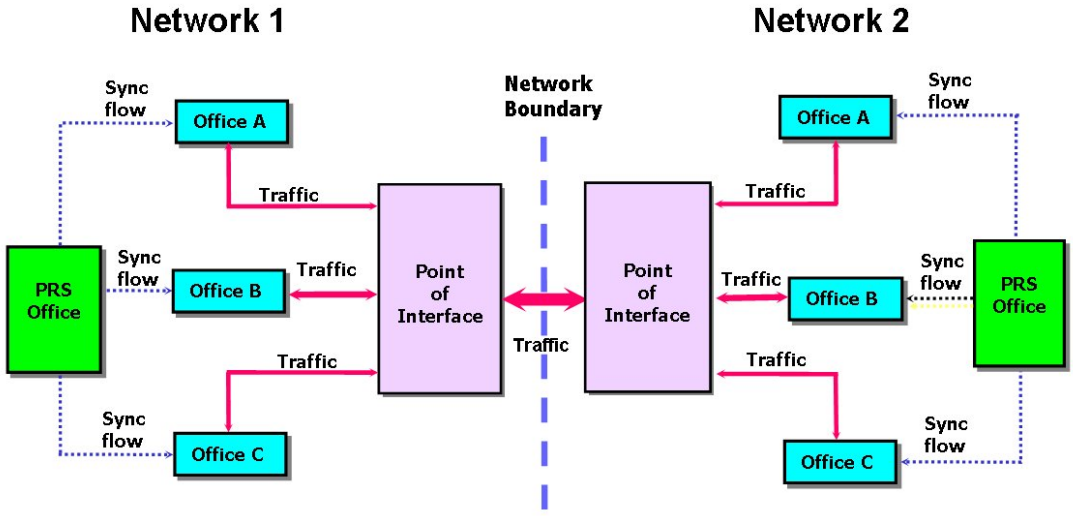


**Fig. 26.** A plesiochronous connection between networks that each maintain their own PRS.

To illustrate this, consider that the traffic exchanged in Fig. 25 is via a DS1/T1 connection [112], which remains the primary digital telephone circuit in the U. S. and Canada. It consists of a digital data stream clocked at a frequency of 1.544 MHz. This data stream is divided into 24 voice channels, each with 64 kHz of bandwidth. Each voice channel is sampled 8000 times per second. When the time difference between the two PRS units exceeds the period of the sampling rate, a cycle or frame slip occurs. This either results in a noisy call or a dropped call. The slip rate, *SR*, is calculated as

$$SR = \frac{T_{samp}}{F_{diff}}, \tag{3}$$

where $T_{samp}$ is the sampling period (125 µs), and $F_{diff}$ is the frequency difference between PRS A and PRS B. If PRS A is high in frequency with respect to UTC by $+1 \times 10^{-11}$ and PRS B is low in frequency with respect to UTC by $-1 \times 10^{-11}$, then the interval between slips is

$$SR = \frac{125 \times 10^{-6}\ \mathrm{s}}{2 \times 10^{-11}} = 6\,250\,000\ \mathrm{s} = 72.5\ \mathrm{days}\ . \tag{4}$$

Figure 27 depicts a slip as an accumulated time or phase error. Here the unit interval (UI) is equal to the period of the DS1/T1 bit frequency, or 647.7 ns. A slip occurs when a complete frame (193 bits) has been lost (647.7 ns × 193 = 125 µs, the period of the sampling rate). Even if one PRS was far more accurate than the requirement, the frequency error in the other PRS would eventually cause a slip, and thus all clocks must maintain good synchronization.

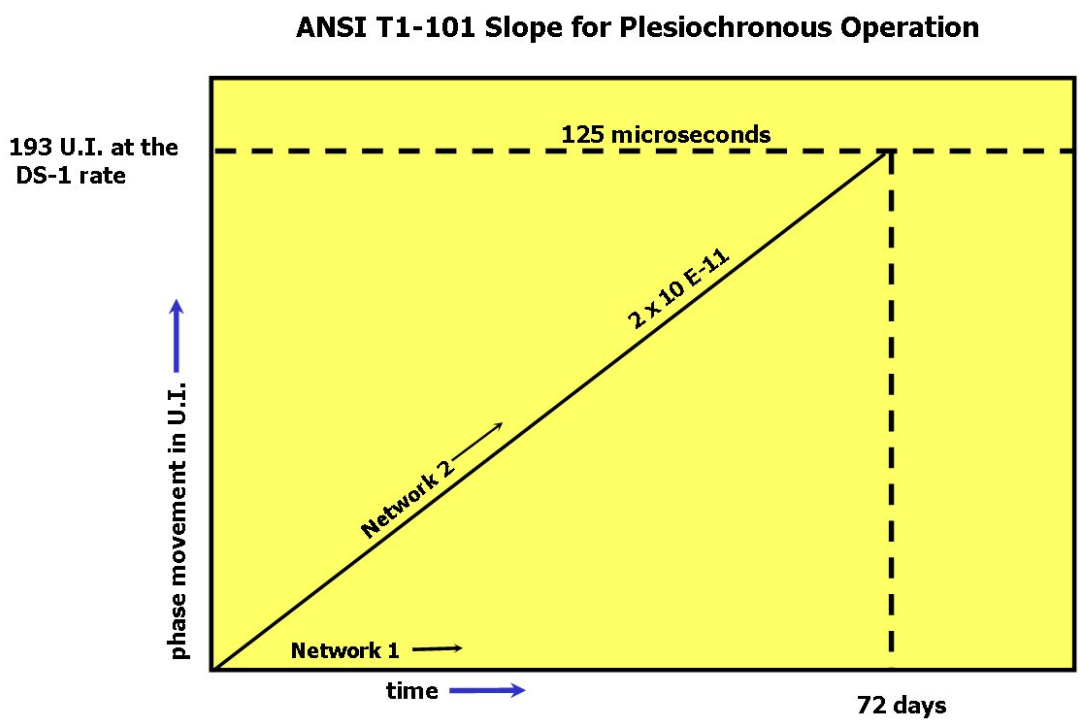


**Fig. 27.** An accumulated time error of 125 µs results in a cycle or frame slip.

Earlier, in Section II.D.3, it was noted that a PRC has a long-term frequency accuracy requirement of $1 \times 10^{-11}$ or better with verification to Coordinated Universal Time (UTC) in the ITU standard [26], and the same specification applied in the ANSI/ATIS standards documents in the U. S. [112]. The ITU also now

has a standard for an enhanced primary reference clock (EPRC) which states that "the maximum allowable fractional frequency offset for observation times greater than one week is 1 part in $10^{12}$, over all applicable operational conditions" [113]. The PRC/ERPC standards can be realized with an autonomous clock, that operates independently of all other sources, or a non-autonomous clock, which is disciplined by "UTC-derived precision signals received from a radio or satellite system" [113]. In most cases, the only autonomous clock that can meet these requirements is a cesium clock, which is typically prohibitively expensive. Thus, a non-autonomous clock, in nearly all cases a GPSDC, typically serves as the PRC.

Time synchronization, and not just frequency syntonization, has become a prerequisite in mobile phone networks. Mobile phone technology originally utilized two types of radio networks to communicate with cellular towers; GSM, an acronym for Global System for Mobile Communications, and CDMA. GSM is far more common with about 90% of mobile phones having GSM capability. GSM is a time division multiple access (TDMA) system that divides a radio frequency into time slots and then allocates slots to multiple calls. Each user has access to the entire frequency channel for the duration of the slot (Fig. 28). It requires the base transceiver station (BTS) to use a single frequency source of absolute accuracy of better than 0.05 parts per million ($5 \times 10^{-8}$) for both the carrier frequency signal and for clocking the time base. However, the time synchronization of the BTS units with respect to each other is optional [114], even though they are usually synchronized due to the presence of a GPSDC at each BTS.

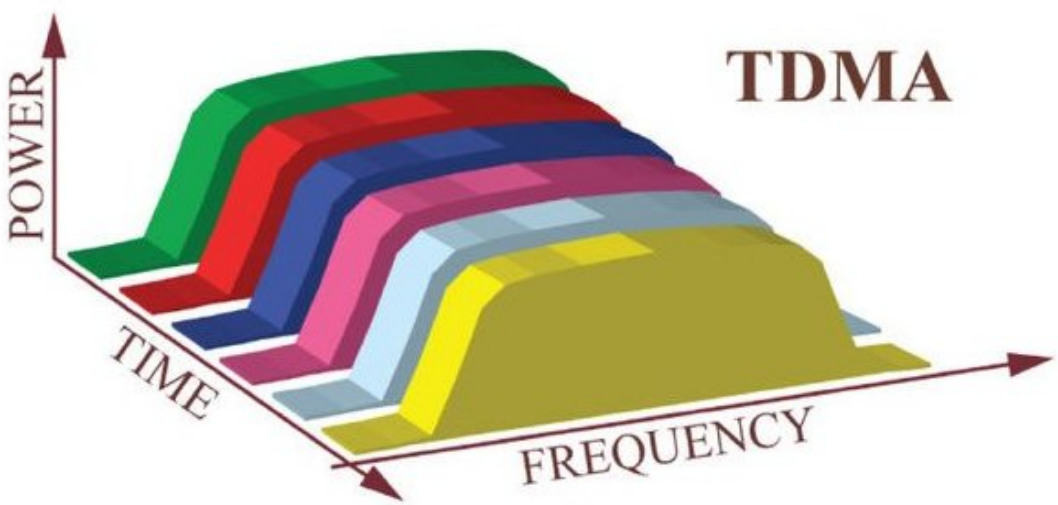


**Fig. 28.** Time division multiple access, users share the same frequency at different times.

In a CDMA system (Fig. 29), the frequency syntonization requirement is the same, $5 \times 10^{-8}$, but the BTS units must be synchronized in time. All users always share the same frequency spectrum and there are no time slots to allocate. However, all transmitted information is encoded by use of spread spectrum codes, and individual users are allocated unique codes that allow them to be identified. This allows the desired signal to be extracted while rejecting everything else as random noise. Every BTS in a CDMA network is aligned to CDMA system time, which originates from GPSDCs. Synchronization should be within ±3 µs, and if the BTS supports multiple simultaneous CDMA channels, within ±1 µs. The holdover requirement is ±10 µs for a period of not less than eight hours, even if the external source of CDMA system time is disconnected [115].

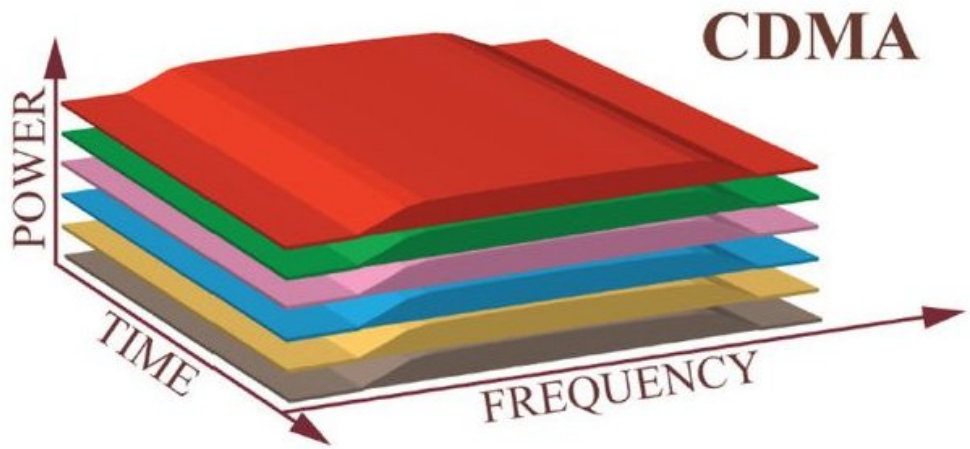


**Fig. 29.** Code division multiple access, users share the same frequency at the same time.

The original GSM and CDMA systems described above represented the 2nd generation of mobile phone technology known as 2G. The 2G networks were the first digital networks, as the original mobile phone networks, now known as 1G, were analog. Today's protocols transfer data at higher speeds and are thus better suited for use as mobile Internet platform, and are somewhat loosely defined as 3G, 4G, and 5G. The protocols are not backward compatible with each other, but some mobile phone providers still support older protocols, including 2G, to keep older equipment operational.

The 3G standards include the Universal Mobile Telecommunications Systems (UMTS), which blended the two technologies. It was based on GSM but utilizes Wideband Code Division Multiple Access (WCDMA) to obtain more bandwidth [116] and can transfer data faster than the original CDMA standard, which was known as IS-95. The 4G standards are defined by the *ITU IMT-Advanced* standard [117] include and include Long Term Evolution Advanced (LTE Time Division Duplex (TDD) or LTE-Advanced) [118, 119] and WirelessMAN Advanced, which has been commercialized using the name WiMAX [120]. The 5G networks, known as 5G New Radio (NR), began deployment in 2019, and follow a new standard that is still under development as of February 2020 [121].

The 4G and 5G networks are based on variations of the orthogonal frequency-division multiple access (OFDMA) technique, which transmits data at low rates across many closely spaced carriers. Because the signals are orthogonal to each other, they do not interfere. This technique makes better use of the spectrum than CDMA, because it uses less bandwidth and thus has better scalability. However, because it is not a spread spectrum technology, but rather a specialized form of multiplexing, OFDMA may be less secure due to the lack of spread spectrum codes. It is also more complicated to implement. The synchronization requirement is similar to CDMA, about 1 µs.

### VI.B Time Synchronization Requirements of Telecommunication Systems

The various mobile phone standards each have time synchronization requirements that are too stringent for free running clocks to meet without frequent calibration, typically near 1 µs, as summarized in Table 7. The table also includes the previously discussed frequency syntonization requirements which can be met by a cesium clock, or even free running rubidium clock in the case of the GSM or CDMA carrier frequency requirement.

**Table 7.** Summary of telecommunications synchronization requirements.

| Network application | Synchronization or syntonization requirements (relative to UTC) |
|---|---|
| **Primary Reference Clock (PRC)** | $1 \times 10^{-11}$ [26, 112] |
| **Primary Reference Time Clock (PRTC)** | 100 ns [122] |
| **Enhanced Primary Reference Clock (EPRC)** | $1 \times 10^{-12}$ [113] |
| **Enhanced Primary Reference Time Clock (EPRC)** | 30 ns [123] |
| **GSM or CDMA carrier frequency** | $5 \times 10^{-8}$ [114, 115] |
| **LTE-TDD (wide area), 4G** | 10 µs [119] |
| **CDMA2000, 2G** | 3 µs [115] |
| **LTE-TDD (home area), 4G** | 3 µs [119] |
| **WCDMA-TDD, 3G** | 2.5 µs [116] |
| **WiMAX, 4G** | ~1 µs [120] |

## VI.C GPS Timing Dependencies of Telecommunication Systems

It seems clear when looking at mobile phone network time synchronization requirements that these systems were enabled by GPSDCs and designed with their usage in mind. GPS is specifically mentioned in nearly all of the standards documents, and time distribution systems under U. S. control that can meet the accuracy requirements without being dependent upon GPS are rare (Table 4). It is also interesting to note that systems have not been designed that require synchronization better than the 1 µs that GPS can provide without calibration, a not so subtle indication that no substitute timing source exists that can provide that type of accuracy at all locations. Therefore, it is easy to see that the mobile phone network has a very high level of dependency on GPS, much higher than the level of dependency in stock exchanges or the power grid.

To obtain much needed timing system diversity, some telecomm providers in the U. S. are turning to global navigation satellite system (GNSS) clocks [124] that receive multiple satellite constellations in addition to GPS, including GLONASS (Russia), Galileo (Europe), and Beidou (China). Table 8 summarizes these systems. There are obvious policy and security arguments against relying upon time signals that are controlled by non-U.S. interests, and there is also the technical argument that multi-constellation reception could be of limited value, because jamming or interference that impacts GPS may impact all GNSS systems with similar frequencies and signal levels. However, network engineers realize that a clock that receives multiple GNSS signals, or even a clock that receives signals on more than one

GPS frequency, will be less susceptible to accidental jamming than the single frequency GPS clocks that are typically in use.

**Table 8.** GPS compared to other global navigation satellite systems.

| System | BeiDou | Galileo | GLONASS | GPS |
|---|---|---|---|---|
| Host Nation | China | European Union | Russia | United States |
| Altitude (km) | 21,150 | 23,222 | 19,130 | 20,180 |
| Orbit Period (hh:mm) | 12:38 | 14:05 | 11:26 | 11:58 |
| Center Frequencies (GHz) | 1.561098 (B1)<br>1.589742 (B1-2)<br>1.20714 (B2)<br>1.26852 (B3) | 1.57542 (E1)<br>1.191795 (E5)<br>1.27875 (E6) | ~1.602 (L1)<br>~1.246 (L2)<br><br>(FDMA, satellites use multiple frequencies) | 1.57542 (L1)<br>1.2276 (L2)<br>1.17645 (L5) |
| Number of satellites | 35 | 30 | 24 | 31 |

The impact of a long lasting, widespread GPS outage on mobile phone networks would likely be staggering, due to the large number of GPSDCs in use. The number of GPSDCs employed in U. S. mobile phone networks already numbers in the hundreds of thousands and may increase dramatically as 5G coverage improves. Mobile phone providers install their BTS equipment at shared cellular sites that are typically located on towers or rooftop platforms, but they do not share equipment. Therefore, a quick glance at any cellular site usually reveals multiple GPS antennas, which either indicates multiple providers or multiple systems operated by the same provider that each require synchronization. CTIA, a trade association that represents the wireless communications industry in the U. S., estimates that 349,344 cell sites were operational in 2018 [125]. Following the plausible assumption that on average at least one, and not more than three GPSDCs are located at each site, results in an estimate of 350,000 to 1 million devices now in service. A widespread rollout of 5G sites is now underway to meet the strong demand for faster data transfer. The 5G rollout involves “small cell” or “micro sites” that cover a limited geographic area and more sites will be needed to provide the necessary coverage. Some analysts predict that the number of cellular sites will triple or quadruple within a few years [126, 127], with perhaps a corresponding increase in the number of GPSDCs.

## VII. Summary

In an attempt to provide a better understanding of the dependency of critical infrastructure systems in the United States on GPS time signals, the first half of this report, contained in Sections I through III, presented the fundamentals and terminology of time distribution systems, exploring concepts including Coordinated Universal Time (UTC) and traceability to the International System (SI) of units, as well as time synchronization, time stamping, frequency syntonization, accuracy, stability, resolution, and the differences between free running and disciplined clocks. From there, the various methods of distributing time from a reference clock so that it can synchronize clocks at other locations were explained, including the one-way, loop-back, common-view, and two-way methods of transferring time. This was followed by a summary of the available public and restricted access time distribution systems that are controlled by U. S. interests.

The second half of the report, Sections IV through VI, was dedicated to examining the time requirements and dependencies of three critical infrastructure sectors; stock exchanges, the electric power grid, and telecommunication systems. Each of these sections was divided into three parts. The first part studied the importance of time synchronization to the sector, the second part studied the sector's time synchronization requirements, and the third part evaluated the sector's dependency on GPS as its timing reference. All three sectors were found to heavily employ and rely on GPS disciplined clocks as part of their everyday operations. However, the level of dependency was found to be highest in the telecommunication sector, particularly in mobile phone networks, where the large number of GPS clocks in place, coupled with the stringent synchronization requirements, would make continued operation without GPS impossible. In contrast, stock exchanges would be likely to continue to operate without GPS, albeit with reduced protection for investors. The daily operation of the power grid would certainly become more labor intensive and difficult, as daily operations would be severely hampered and diagnostic tools would become less useful, but grid operation would likely continue as it did prior to the introduction of GPS.

The key takeaway from this study is that significant GPS dependencies exist in all three sectors, and that all sectors would benefit from improvements in both resiliency and diversity. Resiliency can be improved by establishing standard practices that manufacturers could implement to make GPS clocks less likely to fail, and diversity can be improved by recommending and developing new timing methods and sources to both backup and complement GPS clocks.

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