Precise Time Transfer Concepts

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PRECISE TIME TRANSFER

Precise time and time synchronization are vital for military systems (e.g. tactical communications, navigation systems, weapon-controlled and target tracking/identification systems) to ensure accurate data processing and meaningful, reliable information transmission and reception. It is because mission-critical strikes and decisions are required to be executed and made in a timely manner to maximize "red-force" loss and minimize "blue-force" fatality. Precise time and time synchronization are also critical for various commercial applications and systems (e.g. Time Division Multiple Access (TDMA)-based communications systems, power-grid control systems). It is precise time and network synchronization, not bandwidth that determines the Quality-of-Service (QoS) of future networks.

There are several methods to transfer precise time from highly accurate and stable reference time sources to other clocks in networks to achieve and maintain network time synchronization. Depending on accuracy requirements, specific time transfer methods are selected and implemented. For instance, time transfer via communications satellites (COMSAT), Global Position System (GPS) satellites, and Link-16 tactical networks is for high accuracy requirements. For low accuracy requirements, time transfer over the Internet (i.e. IP networks) can be implemented; some commonly implemented Internet time transfer protocols are Network Time Protocol (NTP), Simple Network Time Protocol (SNTP), and Precise Time Protocol (PTP).

This paper presents an overview of the precise time transfer concept; it also discusses the operational principles of several time transfer methods via satellite and Radio Frequency (RF) links currently implemented in both military and commercial systems and applications.

1. INTRODUCTION

What is time? Even time is commonly used in everyday life, it is not easy to define what time is. Since ancient times till now there have been many definitions with some of them provided below.

"What, then, is time? If no one asks me, I know; if I wish to explain to him who asks, I know not." --- Saint Augustine, circa 400 A.D.

"It defines the temporal order of events."

"It is an element in the four-dimensional geometry of space-time."

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According to Webster's New Collegiate Dictionary time is: "The measured or measurable period during which an action, process, or condition exists"

Precise time is time from a reference time source. A reference time source, also known as a time (and frequency) standard, is a highly accurate and stable source of time (and frequency) standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity. The Coordinated Universal Time (UTC) as derived and maintained by an ensemble of atomic clocks (i.e. Hydrogen maser, Caesium, Rubidium clocks) at the US Naval Observatory (USNO) - denoted as UTC(USNO) is a such a reference time source (and frequency).

As illustrated in Figure 1, precise time transfer is the transmission of time (t_{REF}) from a reference time source to other clocks (i.e. client/slave clocks) in a network so that the client/slave clocks can compute the offset of their local clocks from the reference clocks (ε_1, ε_2, $\varepsilon_{...}$, ε_N) and adjust their clocks accordingly to achieve and maintain network time synchronization.

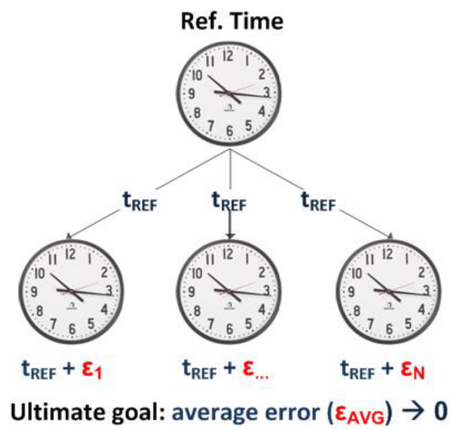


Figure 1: Precise Time Transfer Concept

Precise time can be transferred via direct cable connection, over the Internet networks, by means of navigation and communication systems. Regardless of what methods are employed, the ultimate goal of precise time transfer is to minimize as much as possible the clock error (ε) as depicted in Figure 1.

2. WHY PRECISE TIME AND TIME SYNCHRONIZATION

Precise time and time synchronization are vital for military systems (e.g. tactical communications systems, navigation systems, weapon-controlled and target tracking/identification systems) to ensure accurate data processing and meaningful, reliable information transmission and reception. It is because mission-critical strikes and decisions are required to be executed and made in a timely manner to maximize "red-force" loss and minimize "blue-force" fatality. Precise time and time synchronization are also critical for various commercial applications and systems (e.g. Time Division Multiple Access (TDMA)-based communications systems, power-grid control systems). It is precise time and network synchronization, not bandwidth that determines the Quality-of-Service (QoS) of the future networks.

Clock synchronization within a predetermined accuracy level to a precise time reference is vital for synchronous systems. Some examples are presented below:

1. Communications Systems: time synchronization is to ensure that terminals in a time-based/time-shared communications networks do not overlap or occupy each others' transmission slots. It is to ensure accurate data/information transmission/reception and processing to obtain meaningful data and information.

2. Weapon and Target Systems: to provide precise target identification and strike and to prevent tracking/identification ambiguity.

3. Navigation Systems: to guarantee precise navigation solutions provided to host platforms.

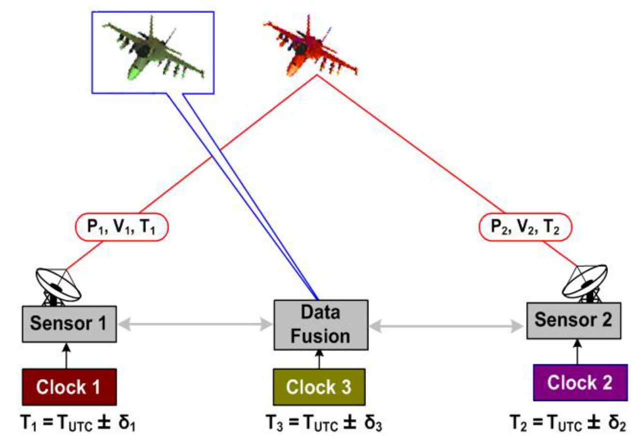
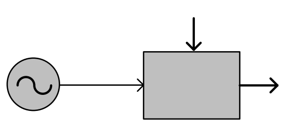


Figure 2: Impact of Asynchronous Network Clocks

As illustrated in Figure 2, if all clocks in target identification and tracking systems are not synchronous, target identification result is ambiguous and not accurate. Target identification is only successful with correct alignment between local and remote track positional data in both time and space.

There are two performance measures with regards to time and frequency - why frequency if time is being talked about? It is because they are related. How are they related? Well, as an example, a clock is generally composed of an oscillator running at a specific frequency and a counting mechanism to produce time from its initially-set time (t_{REF} in Figure 3). As a result, two concepts need to be clearly defined: time synchronization and frequency syntonization.



Clock Equation

$$T(t) = T(t_0) + R(t - t_0) + D(t - t_0)^2 + x(t)$$

t : current time
t_0: time of last update
T: time offset
R: frequency offset
D: frequency drift rate due to aging
x: stochastic error

Figure 3: Clock and Clock Equation

Time synchronization is the process of setting two or more clock in a network to "exactly" the same time. The ultimate goal of any time synchronization scheme is to minimize the offset between a local time and a reference time to achieve the finest accuracy. Time accuracy of a clock depends on the accuracy and stability of its frequency source, and how its time is periodically adjusted with respect to a reference time source.

Time accuracy/offset is defined as the difference between a measured on-time pulse and an ideal on-time pulse that coincides exactly with a reference time (e.g. UTC), see Figure 4, and is the performance matrix of time synchronization.

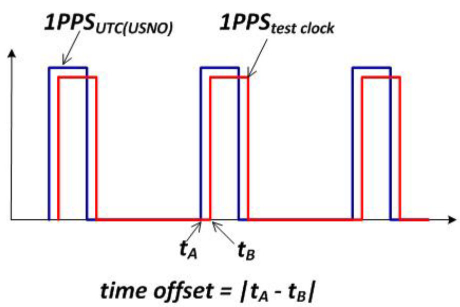


Figure 4: Time Offset/Accuracy

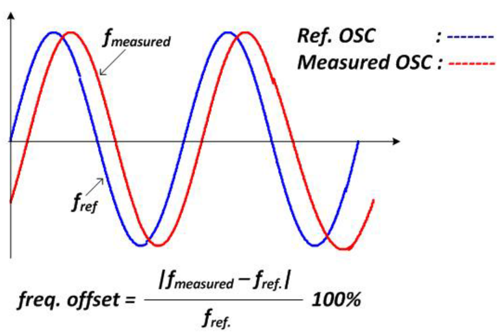


Figure 5: Frequency Offset/Accuracy

Frequency syntonization is the process of setting two or more oscillators in a network to run at "exactly" the same frequency. Frequency accuracy/offset (see Figure 5) is defined as the difference between a measured frequency and an ideal frequency standard with zero uncertainty and is the performance matrix of frequency syntonization. For example, a Caesium oscillator (often referred to as Caesium clock) is a stratum 1 oscillator that has a frequency offset of 1e-11 or better.

3. PRECISE TIME TRANSFER METHOD

There are several methods to transfer precise time from reference sources to networked clocks to achieve and maintain network time synchronization. Depending on accuracy requirements, specific time transfer methods are selected and implemented. Listed below are several time transfer methods. Only some of these will be discussed here due to the scope of this paper.

- ***Primary Dissemination Method***
  - Global Positioning System (GPS) One-way and GPS Common-view Time Transfers
- ***Wide Area Alternatives***
  - Precise Clock (stand-alone) embedded in GPS Receivers
  - Calibrated Precise Atomic and Quartz Clocks
  - Two-Way Satellite Time and Frequency Transfer (TWSTFT)
  - Communications Systems such as SATCOM
  - Loran-C Common View
  - HF (WWV) Time and Frequency Standard Stations
  - Network Time Protocol (NTP), Simple Network Time Protocol (SNTP), Precise Time Protocol (PTP)
- ***Local Area Alternatives Coupled into Tactical Systems***
  - Joint Tactical Information Distribution System (JTIDS)/Multifunction Information Distribution System (MIDS)
  - War-fighting Unit Timing Distribution System (e.g. NAVSSI (Navigation Sensor System Interface))

Amongst the time transfer methods mentioned above, the most accurate one is Two-Way Satellite Time and Frequency Transfer (TWSTFT); the most widely-implemented method over IP networks is Network TimeProtocol (NTP); the most affordable method with high accuracy is one-way GPS time transfer.

4. GPS TIME TRANSFER

GPS satellites disseminate GPS time which is referenced to and traceable to the Coordinated Universal Time (UTC). As a result, one-way and common-view GPS time transfers are the two most popular time transfer methods with affordability coupled with high accuracy. One-way method is widely used by both military and civilian systems while common-view methods are most used between clock and timing labs and facilities.

UTC is a composite time scale comprised of inputs from a time scale derived from atomic clocks and a time scale referenced to the Earth's rotation. The US Naval Observatory (USNO) maintains an ensemble of atomic clocks together with astronomical data to derive its own version of UTC denoted as UTC(USNO).

4.1 One-way GPS Time Transfer

Each GPS satellite contains multiple highly accurate and stable atomic clocks (Caesium, Rubidium) to disseminate GPS time referenced to UTC(USNO). GPS time (also known as GPS system time) coincided with

UTC(USNO) at 0000 hr Jan. 06, 1980 and is not corrected. As a result, it has gradually drifted from UTC(USNO).

The USNO monitors GPS time to provide a reliable and stable coordinated time reference for the satellite navigation system and end-users. GPS time correction parameters are derived and sent to the GPS Master Control Station (MSC) and then up-linked to GPS satellites via the Ground Uplink and Monitor Stations to be embedded in the navigation messages which are transmitted to GPS receivers.

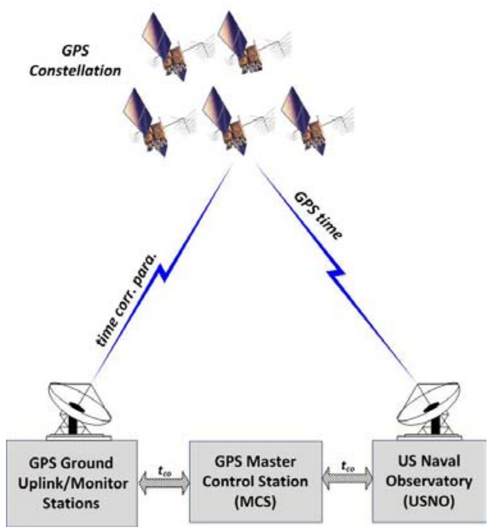


Figure 6: GPS Time Monitor and Correction

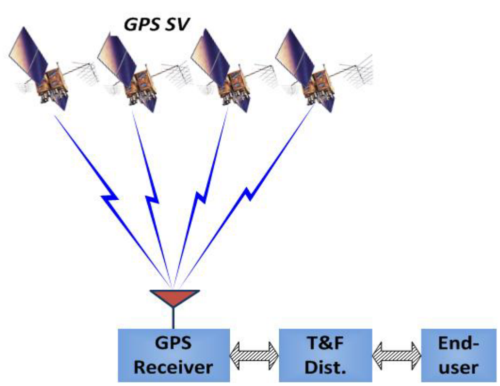


Figure 7: One-way GPS Time Transfer

GPS receiver decodes GPS timing information and time correction parameters from received navigation messages and uses these parameters to steer and correct its locally generated 1PPS pulse to be aligned as close as possible to UTC(USNO). Time-of-Day (ToD) is also derived from the navigation messages. A typical GPS receiver can provide several discrete time pulses and time codes. From the discrete time pulses, frequency standard of stratum 1 accuracy (i.e. accuracy level is better than or equal 1e-11 or 1 part per 100 billion) can also be produced and provided to end-users if required.

4.2 Common-view GPS Time Transfer

This time transfer method is developed by US National Institute of Standards and Technology (NIST) and is widely used by clock and timing labs and facilities.

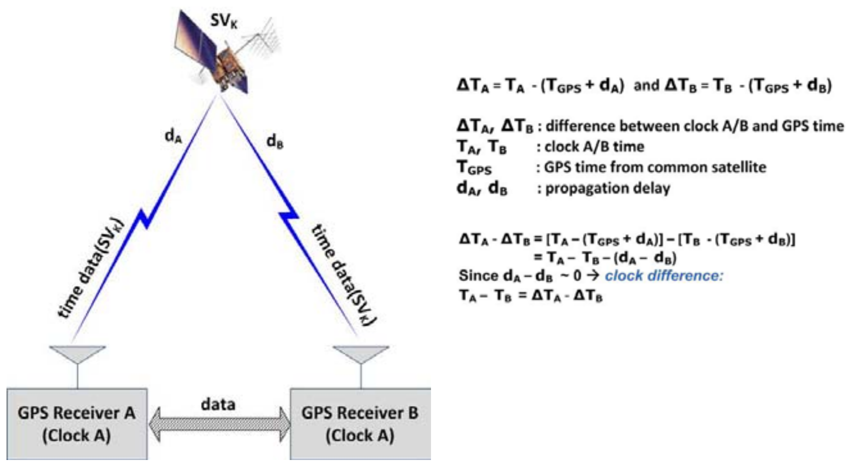


Figure 8: Common-view GPS Time Transfer

As illustrated in Figure 8, both clocks (i.e. GPS receiver-based clocks) simultaneously lock onto a common in-view GPS satellite and derive its own GPS time and then compute the time difference between each clock time and GPS time.

The delta-times are exchanged between 2 clocks from which the time difference between 2 clocks is obtained and each clock can adjust itself toward synchronization.

4.3 GPS Precise Time Vulnerability

It is well-known that GPS receivers are extremely vulnerable to intentional/unintentional RF interferences from, say, radio/TV transmitters and GPS-jamming emitters. When such interference occurs, GPS time service is disrupted resulting in other systems that required GPS time to not operate properly.

Since GPS is increasingly employed as the primary time and frequency dissemination method for military and commercial systems and applications, relying only on GPS as a sole means of precise time and frequency transfer may not guarantee service continuity and/or Quality-of-Service (QoS) at the highest quality level. GPS service disruption and discontinuity due to interference may seriously impact the operations of systems such as navigation, communications, target tracking that rely on GPS for time and frequency reference signals.

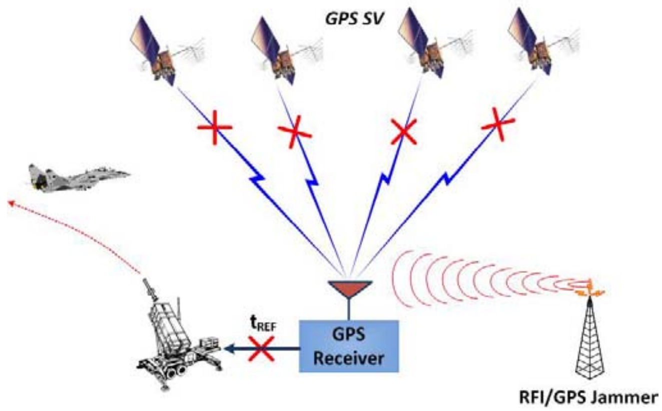


Figure 9: GPS Precise Time Disruption

4.4 GPS Precise Time Distribution

GPS time (and frequency) can be directly delivered to end-users via direct cable connections. However, several issues arise:

- The number of users are limited due to limited output ports from the T&F Source
- Close proximity between source and users required due to signal degradation due to transmission
- Service continuity is not guaranteed due to cable breakdown, signal loss, network conditions
- Direct distribution method does not always provide the best performance in terms of accuracy; this method is very vulnerable to system single-point-of-failure due to single time source (i.e. GPS receiver).

Figure 10 illustrates a possible architecture for the distribution of GPS precise time that guarantees service continuity (single-point-of-failure elimination) at the highest level of accuracy and reliability.

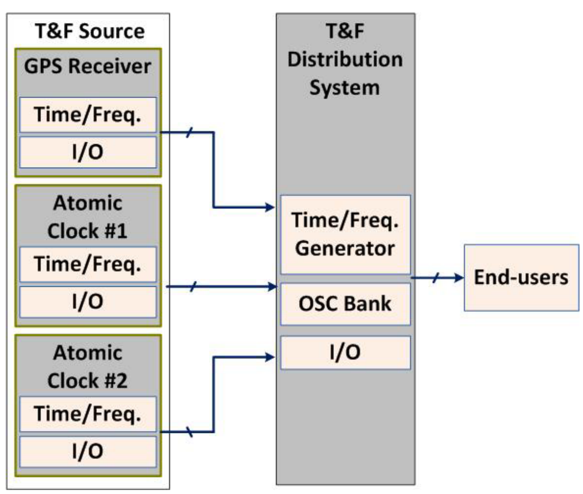


Figure 10: GPS Precise Time Distribution Configuration

The architecture is implemented with two main components: the Time and Frequency (T&F) Source and the T&F Distribution System.

1. T&F Source

This is the source of precise time and accurate frequency reference standards from which a variety of time and frequency signals can be generated to meet various end-user requirements.

Since GPS is vulnerable to RF interferences, the T&F source is also composed of non-GPS time sources (e.g. Caesium, Rubidium clocks) to prevent single-point-of-failure and service disruption. Multiple sources also enable integrity and performance monitoring based on the three-cornered hat principle.

The GPS and non-GPS time sources monitor each others' time qualities and provide self-correction for degraded source without human intervention and thus, minimize service disruption.

T&F Distribution System

The T&F Distribution System accepts reference signals from the T&F Source, these signals are then passed through the integrity and performance monitoring process and the best signal in terms of accuracy and stability is selected and used to generate a variety of time and frequency signals for end-users. The generated T&F signals include, but not limited to, 1, 5, 10 MHz, 1PPS, Time Code, T1/E1, T3, etc. and others, as required.

Configured with high-quality single or dual oscillators (i.e. oven-controlled crystal oscillator, Rubidium oscillator), the T&F Distribution System also possesses hold-over capability to maintain highest Quality-of-Service (QoS) when the T&F Source is completely out-of-order.

5. LINK-16 PRECISE TIME TRANSFER

5.1 Overview

Link-16, also known as TADIL-J, is the Tactical Communications Networks with high capacity data communications and anti-jam capability. It is deployed by US Joint Forces as well as NATO Allies for many air and sea platforms.

Link-16 networks are configured with either Joint Tactical Information Distribution System (JTIDS) or Multi-function Information Distribution System (MIDS) terminals. Time Division Multiple Access (TDMA) transmission protocol with Frequency Hopping Spread Spectrum (FH-SS) modulation technique is the communication scheme for Link-16 networks.

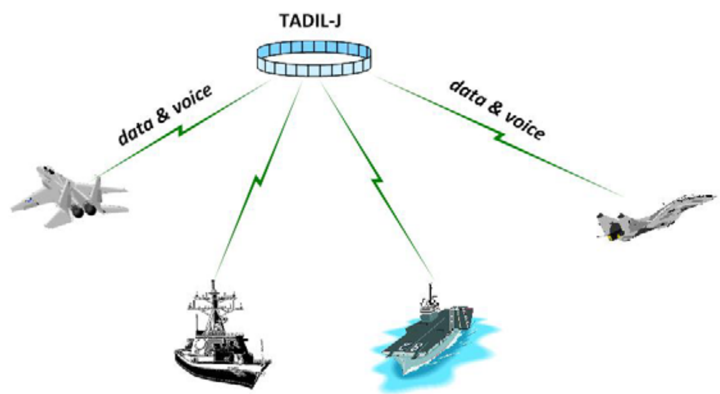


Figure 11: Data and Voice Transmission Over Link-16 Networks

Link-16 network participants are capable of transferring precise time for absolute or relative network time synchronization. As with most other time transfer methods, Link-16 networks employ the Round Trip Timing (RTT) algorithm to achieve synchronization (see Figure 12).

To transfer time over Link-16 network, a terminal is designated as the Network Time Reference (NTR) and it may get time reference from an External Time Reference (ETR) source (e.g. GPS). This terminal is called the ETR/NTR terminal and is the reference time source from which all participants in a Link-16 network will obtain time to achieve and maintain network synchronization.

RTT algorithm is implemented to transfer precise time between the NTR or ETR/NTR terminal to other network participants (i.e. clients).

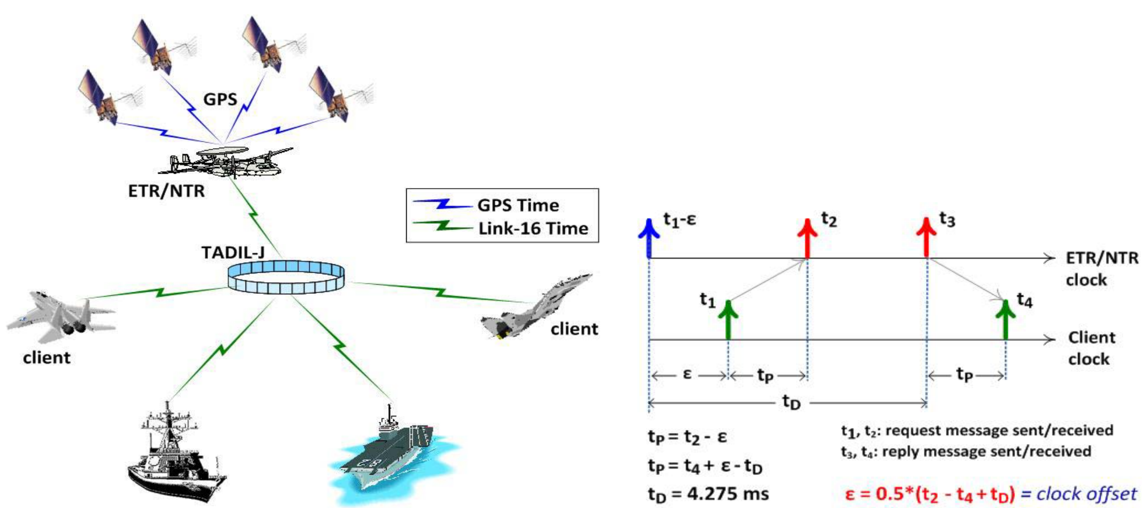


Figure 12: Precise Time Transfer Over Link-16 Networks with RTT Algorithm

5.2 Link-16 / GPS Integration

Since Link-16 terminals are capable of precise time transfer and are jam-resistant, Link-16 can provide precise time to other platforms; such as, end-users that rely on GPS for precise time but have to operate in GPS-denied environments (Figure 13) due to jamming or GPS service unavailability due to equipment and system failures.

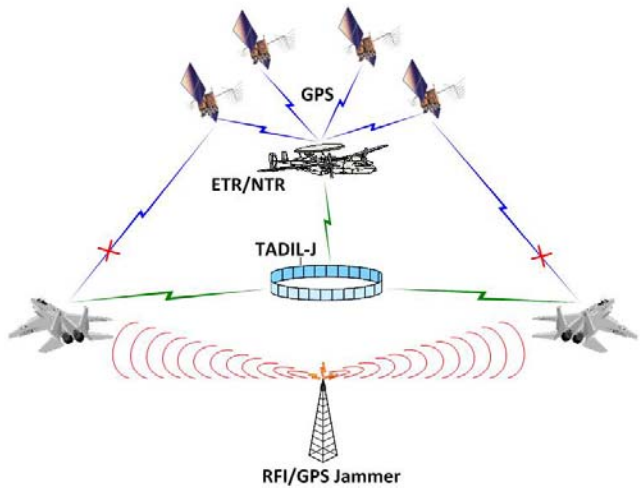


Figure 13: Link-16/GPS Integration in GPS-denied Environment

Time transfer capability of Link-16, JTIDS Class II terminals in static and dynamic environments was performed demonstrated by the GPS and Navigation Division (code 231) of the Spawar System Center – San Diego in July 2005 and Feb. 2006 respectively under the sponsorship of the Office of Naval Research (ONR) – Dr. John Kim, ONR-312. The findings from the demonstrations are:

- Link-16 (JTIDS Class II) is fully capable of transferring precise time
- Link-16 is a sturdy system; Link-16 limits input errors
- Link-16 can assist other systems in a GPS denied environment by mitigating against their GPS vulnerabilities
- Link 16 meets critical military requirements for time transfer

6. TWO-WAY SATELLITE TIME TRANSFER

Two-way Satellite Time and Frequency Transfer offers the highest level of accuracy for the most stringent precise time requirements. To transfer time via TWSTFT method, both terminals (and clocks) simultaneous transmit a time-code signal (e.g. 1PPS pulse) to one another. Each terminal measures the time interval between the transmission of its local 1PPS pulse and the reception of the remote 1PPS pulse.

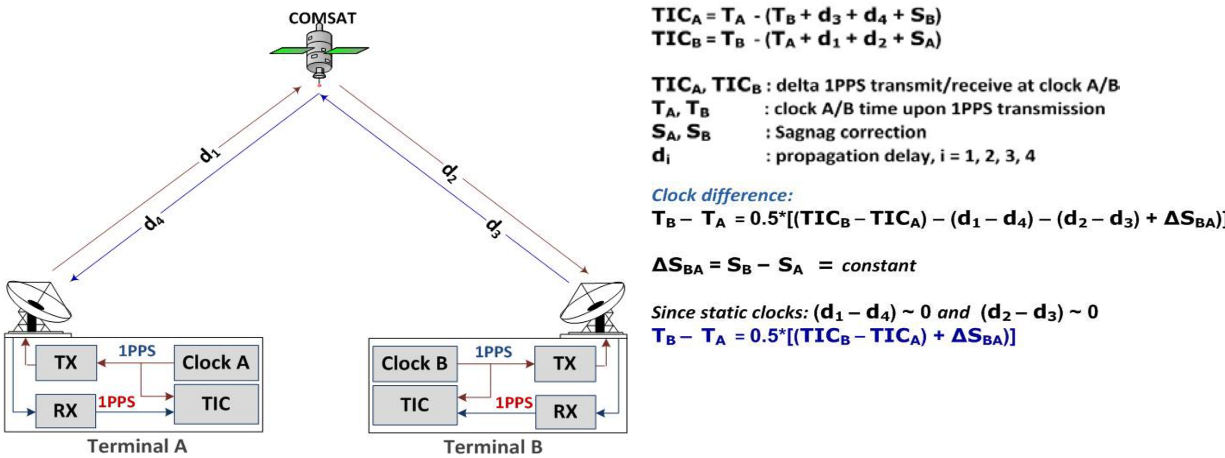


Figure 14: Two-way Satellite Time and Frequency Transfer – Static Clocks

Measurement data are exchanged between terminals to compute offset between 2 clocks, then each clock will adjust its clock accordingly to achieve time synchronization.

Figure 14 illustrates the case of TWSTFT in which both terminals are static. In this case, the propagation delays between terminals are cancelled out and the Sagnag effect is a constant which can be calculated and compensated for in the computation of clock offset. However, if at least one of the terminals is dynamic; propagation delays are not completely cancelled out and Sagnag effect is time-varying as illustrated in Figure 15.

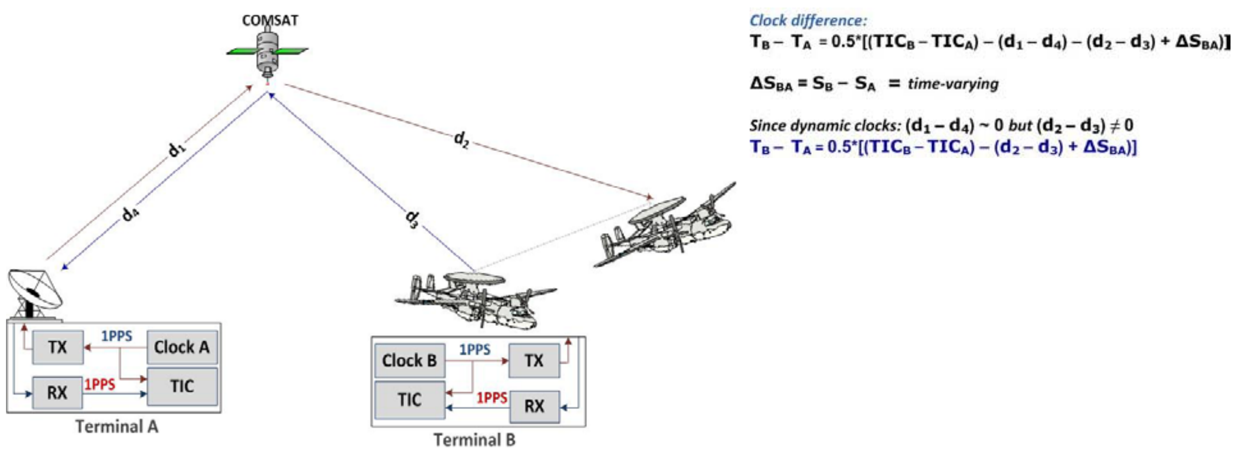


Figure 15: Two-way Satellite Time and Frequency Transfer – Dynamic Clock(s)

Some notes from the TWSTFT method:

- For high accuracy, propagation delay difference between 2 paths must be minimal → radial motion of satellite must be minimal during measurement interval.
- For static clocks with geo-synchronous satellite, all propagation delays are cancelled out → best case.

7. CONCLUSION

- Precise time and time synchronization are required to ensure accurate data/information transmission and reception and data processing. Without precise time, mission-critical systems and applications may not operate properly.
- There are several methods to transfer precise time from accurate and precise sources to other clocks to achieve and maintain network time synchronization. Precise time can be transferred via communications satellites (COMSAT), GPS satellites, and Link-16 tactical networks. Time can also be transferred over the Internet networks.
- As technology advances (i.e. computers run faster, digital bandwidth is wider), precise time requirements become more and more stringent.
- Precise time and network synchronization, not bandwidth, will determine the service quality of future networks.

8. BIBLIOGRAPHY

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