DATA AND TIME TRANSFER USING SONET RADIO

Gary M. Graceffo
HRB Systems
Linthicum, Maryland 21090

Abstract

The need for precise knowledge of time and frequency has become ubiquitous throughout our society. The areas of astronomy, navigation and high-speed wide-area networks are among a few of the many consumers of this type of information. GPS has the potential to be the most comprehensive source of precise timing information developed to date; however, the introduction of Selective Availability has made it difficult for many users to recover this information from the GPS system with the precision required for today's systems.

The system described in this paper is a "SONET Radio Data and Time Transfer System." The objective of this system is to provide precise time and frequency information to a variety of end-users using a two-way data and time-transfer system. Although time and frequency transfers have been done for many years, this system is unique in that time and frequency information are embedded into existing communications traffic. This eliminates the need to make the transfer of time and frequency information a dedicated function of the communications system.

For this system, the Synchronous Optical NETwork (SONET) has been selected as the transport format from which precise time is derived. SONET has been selected because of its high data rates and its increasing acceptance throughout the industry. This paper details a proof-of-concept initiative to perform embedded time and frequency transfers using SONET Radio.

OVERVIEW

The SONET Radio Data and Two-Way Time-Transfer system (TTS) described in this paper is used to perform point-to-point data-and two-way time transfers between a master control site and a remote site. Each of these sites uses an ensemble of cesium clocks to maintain precise time and frequency. For the remote sites to perform as required, time-transfers must occur on a regular basis as a dedicated on-site maintenance function to maintain synchronization with the master control site. The use of embedded time-transfer technology will replace this dedicated function and allow continuous, dedicated, time transfers.

Synchronous Optical NETwork (SONET) is a Bellcore term for the Synchronous Digital Hierarchy (SDH) standardized by the International Telegraph and Telephone Consultative Committee (CCITT) in Europe and Asia. SONET is a high-speed fiber optic transport standard which will eliminate the different transmission schemes and rates used in Japan, Asia and the United States. SONET is a transport interface and method of transmission only; it is not a network in itself[1]. SONET is gaining wide acceptance in the telecommunications industry; therefore, it can be used to perform time transfers over many networks. The high data rates provided by SONET are very desirable for the application of time transfer. SONET data rates range from OC-1 (51.84 Mbps) to OC-48 (2.488 Gbps) with a theoretical upper limit of 0C-255 (13 Gbps). SONET is suitable for use in a broadcast medium (SONET Radio) as well.

This system is a proof of concept to demonstrate the use of an overhead byte in the SONET frame header to convey time information. The concept of using a header byte for time transfer has been detailed in a paper by M. Kihara entitled "SDH-Based Time and Frequency Transfer System"[2]. For this proof-of-concept demonstration, the synchronization will be performed during the exchange of routine message traffic between the master control site and a remote site. Due to the limited amount of transponder band width the initial proof-of-concept effort will be done at a sub-SONET rate. The modems that bridge the two networks will run at a data rate of 10 Mbps. The two networks on which the modems reside will run at an OC-3 data rate. It is anticipated that the time-transfer accuracy will be better than 3 nanoseconds and will have a frequency instability of 7×10^{-12} at 1 second.

In order to reduce the technical risk and to keep the development costs down, the system is designed to be modular and is comprised primarily of commercial-off-the-shelf (COTS) components. The hardware and software that comprise the communications encoder and decoder (COMDEC) unit are the only custom-designed components in the system. To maintain the philosophy of modularity, the same software and hardware are used at both the master and remote sites.

This system is the first phase of a multi-phase study. The overall goal is to embed time transfer information into the SONET overhead bytes in a variety of transmission mediums. The method has already had success over optical networks in Japan[2].

TIME CODE DEFINITION

The Timing Solutions Corporation (TSC), working with Judah Levine of NIST (National Institute of Standards and Technology), has detailed an approach using a single unused byte in the SONET frame header to convey the time-code[3]. TSC has attempted to maximize compatibility with a Japanese proposal to the ITU-R Working Party 7A regarding network time and frequency transfers. This system attempts to maximize compatibility with the approach set forth by TSC; however, some modifications to their approach are necessary due to bandwidth limitations in the radio link.

A SONET frame consists of two parts, a header and a synchronous payload envelope. The payload is unacceptable to convey time information because the data packets "float" within the envelope area[3]. The header, however, is not subjected to reallocation. For this reason, to achieve accurate time transfers, the header must be used to convey the timing information.

The time code is transmitted as a block of five words. Each word is represented by five bytes. The most significant bit in each time-code byte functions as an on-time marker to signal the start of a new time code sequence. The remaining seven bits in each byte are used to transmit the time-code sequence. A complete time-code sequence contains administrative information, modified Julian day (MJD) and time of day (TOD) to hundredths of a nanosecond. The time code length is flexible and can grow to meet future needs.

The first word of the time-code contains administrative information. This information includes: flags, sender's identifier and recipient's identifier. Flags include: message synchronization, primary/secondary identifier and master/slave identifier. The second word contains a message synchronization flag, message type field, a descriptive message code (ccc) field and the most significant 28 bits of the time code. There are currently four types of messages defined. These message types are:

Next frame contains a time mark (1111)
NULL (1110)
Frequency Information (0001)
Time Information (0000)

The message type (1111) is used by the hardware and software to prepare to receive an on-time time marker to which the hardware must be synchronized. The message type NULL (1110) is used when time or frequency information is not being transmitted or to end the transmission *of a time code.* Message types (0001) and (0000) are used to identify the transmission of frequency or time information respectively. There are currently sixteen ccc codes identified. These codes are used to identify the type of frequency or time information being transmitted (i.e. absolute time, relative time, leap second notification, etc.)

The third word and subsequent words have the same format. Word three of the time code contains: a message synchronization flag, additional ccc information and 32 bits of time or frequency information. The third word is repeated until the entire time code is transmitted. Table 1 details the time-code sequence.

SYSTEM DESCRIPTION

The SONET Radio Data and Two-Way Time-Transfer System is a node on a network. As shown in Figure 1, its function is to perform data and two-way time transfers between two networks. Figure 2 illustrates the architecture of the SONET Radio Data and Two-Way Time-Transfer System. The system has five component parts: Antenna unit, Transceiver unit, Modem, COMDEC unit, and the Ensemble. The communications decoder/encoder (COMDEC) unit illustrated in Figure 3 is the heart of the data and time-transfer system. The unit is designed to interface a modem to a SONET network while building or recovering a time code. The COMDEC unit is responsible for removing time information from the SONET header, passing the received time-code information to a personal computer (PC) and providing a 1 pulse per second (PPS) reference signal which is coherent with the received time-code information. Control of the COMDEC unit is through an external interface using a PC.

The procedure to initiate a time-transfer is as follows: the master control station (reference station) and the remote site each exchange time codes simultaneously. Each site sends a message type of (1111), which indicates that the next frame contains an on-time mark. The message type (1111) is used to reset the hardware and prepare to synchronize to the on-time mark. The next time byte that is transmitted has the most significant bit in the time-code byte set to 1, indicating the start of a time-code sequence. The following time-code bytes contain the message type, ccc code and the time information. The most significant bit of each subsequent frame is set to 0, indicating the on-time marker is not present. When a time-code transmission is completed a me ssage type of "NULL" is transmitted, indicating the end of transmission.

When the COMDEC unit is in transmit mode the SONET frames to be transmitted are retrieved from the network by the SONET interface module and stored in the transmit buffer. The PC loads the transmit buffer with part of the time-transfer information and signals the digital signal processor (DSP)/controller microprocessor to begin transmission. The DSP obtains the fractional seconds part of the time code from the Transmit Time-Tag Unit and completes the time code with this information. The Transmit Frame Controller unit reads the Transmit Buffer a word at a time and sends it to the modem to be modulated, using binary phase shift keying

(BPSK), and converted from a baseband signal to an intermediate frequency (IF) of 70 MHz. The transceiver converts the IF signal to Ku-band for transmission.

When the COMDEC unit is in receive mode, it receives a bit stream that has been recovered by the modem. The COMDEC unit reconstructs the SONET frames from the recovered bit stream and records the embedded time code. The time code is placed in the receiver buffer for post processing by the PC. The time code is also loaded into a counter in the COMDEC unit. The counter is clocked using a submultiple of the recovered carrier. The counter generates a 1 PPS signal that is coherent with the transmitting site's ensemble. A Time Interval Counter (TIC) external to the COMDEC unit is used to measure the phase difference between the recovered 1 PPS signal and the station 1 PPS signal. A PC records the phase difference between the two 1 PPS signals. The recovered payload is placed in a SONET frame and the frames are sent to the appropriate devices on the network.

Once the measurement process has been completed, the two sites exchange measurements so that the relative phase offsets may be determined. Measurements are exchanged by placing the measurements in the SONET header and using the appropriate message type to identify the type of information being transmitted.

The ensemble is used to provide the data and time-transfer system with precise time and frequency information. All signals in the data and time-transfer system are coherently derived from the ensemble. The ensemble consists of a suite of three cesium clocks, two GPS receivers and a computer to continuously steer the master clock in frequency. The ensemble has a long-term instability of 7×10^{-14} at one second.

RECIPROCITY

Two-way time transfer is used so that reciprocity in the path may be assumed. The measurements made at each site using the time interval counter reflect the phase difference of the two 1 PPS signals and the propagation delays. If these measurements are differenced, then the delay terms will cancel, leaving a residual of the phase difference between the two station clocks. This may be expressed as follows:

$$R(B) = B - A + TdAB \quad \text{(at site B)} \tag{1}$$

$$R(A) = A - B + TdBA \quad \text{(at site A)} \tag{2}$$

where

$R(B)$	=	time difference displayed on time interval counter at remote site (B)
$R(A)$	=	time difference displayed on time interval counter at the master site (A)
A	=	time displayed on clock A
B	=	time displayed on clock B
$TdAB$	=	aggregate of systematic delays between site A and site B
$TdBA$	=	aggregate of systematic delays between site B and site A
$A - B$	=	phase difference between clock A and clock B
$B - A$	=	phase difference between clock B and clock A

$$TdAB = TdTA + TdAS + TdTB + TdsB + TdrB \tag{3}$$

where

$TdTA$	=	delay in the transmitter at site A
$TdAS$	=	path delay from site A to satellite
$TdTB$	=	transponder delay in the direction A to B
$TdsB$	=	path delay from satellite to site B
$TdrB$	=	delay in the receiver at site B.

The delays in the receiver and the transmitter are removed through calibration. If reciprocity is assumed, then path delays and the transponder delays are equal in both directions and, therefore, cancel out. If we assume reciprocity and the sites exchange time interval measurements (i.e. $R(A)$ and $R(B)$), then each site can find its phase offset relative to the other site. If it is assumed the master station is the reference, then the remote site can determine its offset from the master clock.

The errors in the phase measurements made between the two stations are from three sources; they are: nonreciprocity in the path, noise in the measurement system and station calibration. The anticipated accumulated error as shown in Table 2 is expected to be a 2.5 nanoseconds. The primary contributor to the nonreciprocity in the system is the transponder path. This is because the upper part of the channel in the transponder will be used in one direction and the lower part of the channel will be used in the other direction. The phase ripple across the entire channel is a few nanoseconds. In order to null this effect, the transmission paths will flip-flop between the upper and lower channel in each direction. This will null the effects of transponder nonreciprocity and reduce the phase error to less than a nanosecond. Therefore, the goal of 3 nanoseconds accuracy is attainable.

SUMMARY

Two Data and Embedded Time-Transfer Systems using a Radio SONET transport format will be built and tested. These systems are nodes on two networks and will function as a bridge between the two networks. These networks exchange data on a daily basis and perform continuous time transfers in an existing communications link. The time-transfer information needed by each site will be embedded in the SONET header during routine site-to-site communications. It is anticipated that time transfers on the order of 3 nanoseconds are very achievable with a frequency instability of 7×10^{-12} at one second. Testing of the system will occur, over an RF path, in the fall of 1996.

REFERENCES

[1] D. Spohn 1993, **Data Network Design** (McGraw Hill, New York).

[2] M. Kihara, and A. Imaoka 1995, *"SDH-based time and frequency transfer system,"* Proceedings of the 9th European Forum on Time and Frequency (EFTF), March 1995, Besançon, France.

[3] S. Stein 1995, *"Architecture of a two-way time transfer system using SONET OC-3 facility interface"* (Timing Solutions Corporation, Boulder, Colorado).

TIME TRANSFER FRAME FORMAT

WORD NUMBER	DEFINITION	RANGE
Word 1		
Byte 0		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6	1 for primary, 0 for secondary	
bit 5	1 for master, 0 for slave	
bit 4-0	Master/Slave identifier	
Byte 1		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-0	Sender's ID	
Byte 2		
bit 7	Message synchronization	
bit 6-0	Recipient's ID	
Bytes 3-4		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-0	Reserved	
Word 2	Time and frequency information	
Byte 0		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-4	Reserved for additional information (ccc)	
bit 3-0	Message type	
Byte 1-4		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-0	Most significant 28 bits of time/frequency information	MJD 28 most significant bits.

Table 1

TIME TRANSFER FRAME FORMAT(CON'T)

WORD NUMBER	DEFINITION	RANGE
Word 3-0		
Byte 0		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-4	Reserved for additional (ccc) information	
bit 3-0	Most significant 4 bits of 32 bit word	MJD 4 Least significant bits
Bytes 1-4		
bit 7	Message synchronization	
bit 6-0	7 bits of 32 bit word most significant to least significant order	1 msec<= T_m <= 86400 sec 28 most significant bits of T_m
Word 3-1		
Byte 0		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-4	Reserved for additional (ccc) information	
bit 3-0	Most significant 4 bits of 32 bit word	4 least significant bits of T_m
Bytes 1-4		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-0	7 bits of 32 bit word most significant to least significant order	.25 psec <= T_p <= 1 msec 28 most significant bits of T_p
Word 3-2		
Byte 0		
bit 7	Message synchronization	1: on-time marker 0: all other times
bit 6-4	Reserved for additional (ccc) information	
bit 3-0	Most significant 4 bits of 32 bit word	4 least significant bits of T_p

Table 1 (con't)

ERROR ANALYSIS

Objective is a time-transfer with 40 nanoseconds (40,000 picoseconds) of error

$$\theta_E = nonreciprosity + calibration\_errors + measurement\_noise$$

Error sources	Magnitude (picoseconds)	
Station Calibration	200	For both stations
Nonreciprocity in path	-	
Ionospheric nonreciprocity	100	For Ku band
Tropospheric delays	<<100	For Ku band
transponders*	2000	
Measurement system	100	

	2500	

* - This can be eliminated with transponder multiplexing

Table 2

INTERNETWORK COMMUNICATION USING SONET RADIO

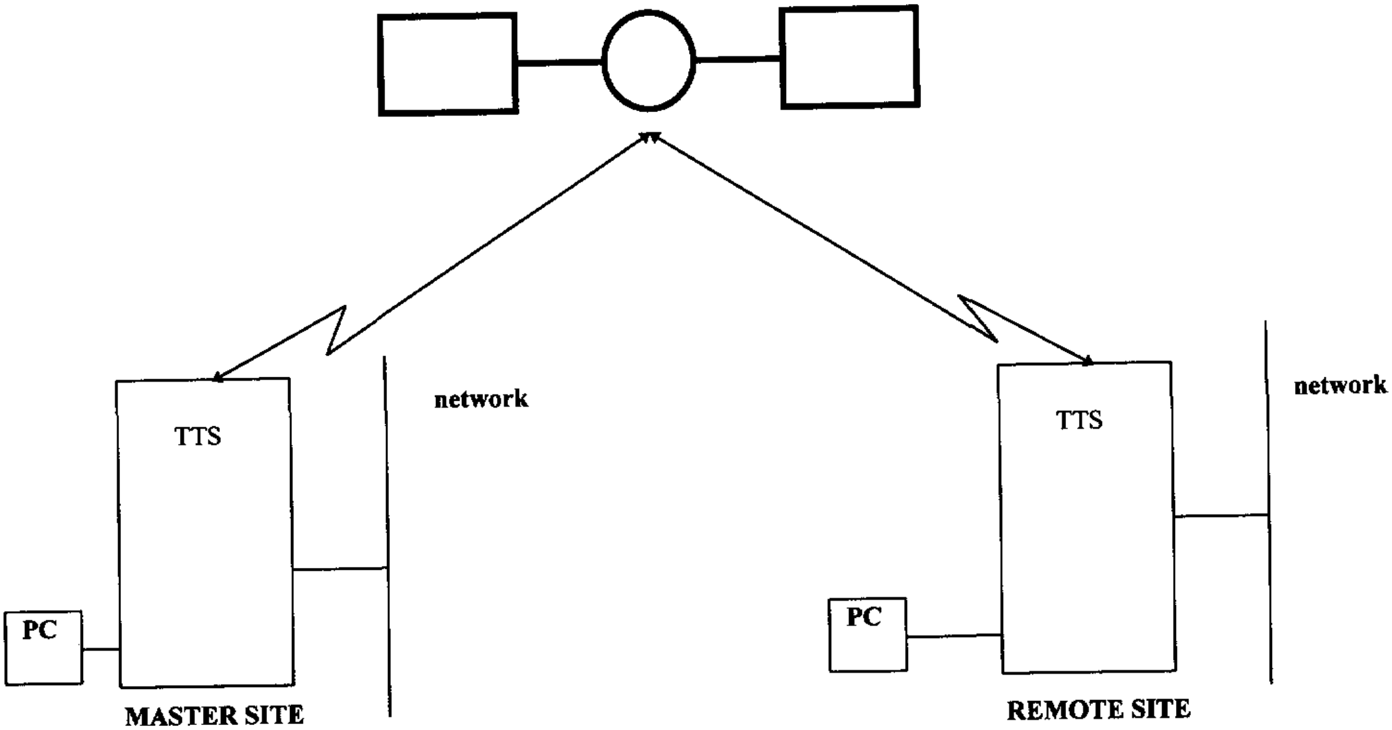

Figure 1

SONET RADIO DATA AND TIME TRANSFER SYSTEM

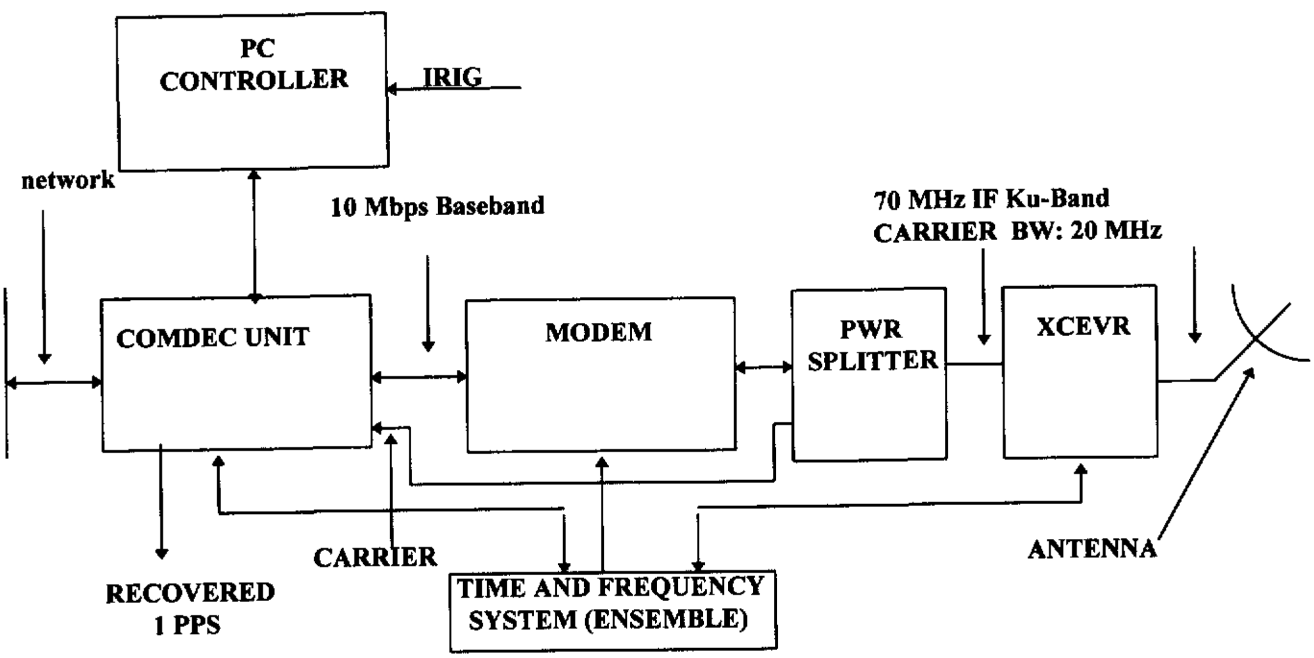

Figure 2

COMDEC UNIT

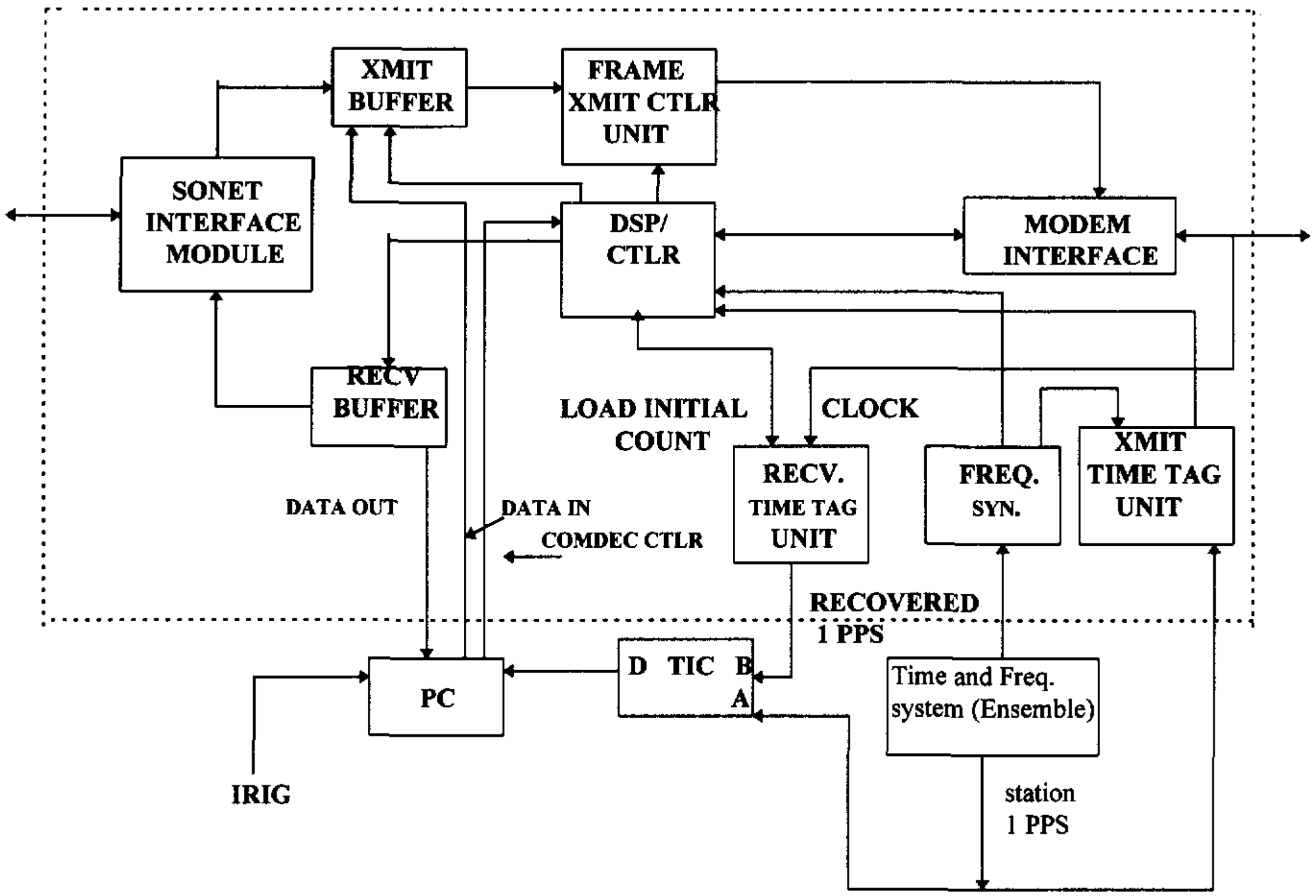

Figure 3