Systematic Designing of Store and Forward Communication Payload for LEO Satellite Systems

Dariush Abbasi-Moghadam
Electrical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran,
Email: abbasimoghadam@uk.ac.ir

ABSTRACT:
The purpose of this paper is designing a communications system and the required protocols for store and forward (S&F) payload of a LEO satellite. Considering users' dispersion in diverse places, split channel reservation multiple access (SRMA) technique, is applied through users to access the uplink channel. Different modulation methods are analyzed and PSK modulation and non-coherent FSK modulation are suggested for payload downlink and uplink, respectively. An error detection technique based on Reed-Solomon (255, 233) is used in the payload to improve the link performance and SR-ARQ approach is selected which is more efficient than other ARQ techniques. Moreover, communication protocols of the users' network, file transmitting to the satellite and file receiving from that along with their implementation are explained in terms of software. Finally, an appropriate hardware is proposed for this subsystem. Comparison of our design and the design strategy suggested in [4] show that onboard hardware complexity of current paper is less than [4]. Furthermore, our coding, modulation and protocol and Doppler compensation scenario is more efficient than [4].

KEYWORD: Store and forward payload, satellite, SRMA, protocol, ARQ.

1. INTRODUCTION

Satellite systems are very well-suited to support data applications and services. Huge amount of data is easily transferred via satellite avoiding the congestion of terrestrial networks, for a fully global transmission. Data can be stored on-board and forwarded in a subsequent period of time, with an acceptable delay in most applications. The class of store and forward satellites works on this principle [1]. Store-and-forward (S&F) communication systems using low earth orbit (LEO) satellites are very suitable for simple and low-cost global data transmission. The missions of these satellites includes sending e-mail between different users, remote communications coverage, collection of information from different sensors, studying different patterns such as immigration of birds, environmental protection and point to point and point to multiple points communication during time period of ground disconnection. In other words, S&F satellites have been conceived to forward little data volumes. Furthermore, a system in which relaying packets of high speed data rate within a few hours is possible, can provide not only simple mail delivery services but can also transmit large files such as still pictures, computer image data, and news sources all over the world. These services provide very helpful ways of supplementing communication infrastructures in developing countries, and providing a communication tool for remote areas or scientific observations [2]. A broad range of services can be conceived and provided by mean of S&F satellites. Some applications such as file transfer on-demand, data transfer to/from remote sites, military applications are telemedicine. Such store and forward satellites can be used as a communication infrastructure for sensor networks [3].The design needs to be relatively inexpensive while at the same time is computationally robust. It must provide the necessary interfaces for each subsystem and also consume limited power. S&F satellites are enabled to collect and forward huge data volumes for new applications and services [2]. Design of such systems is similar to one explained in this paper however, in their proposed design required power and bandwidth is increased. Such systems could easily be integrated with terrestrial networks, which is a privilege for the overall system. Unfortunately, LEO satellite footprint is small and therefore many satellites are required for a global coverage with short time delay. Moreover, in this case handover procedures are complex in order to comply with the real-time nature of the service.

Ground station sends digital information to LEO satellite, the satellite stores the message and the ground station retrieves message destination. When the data is received and stored in the payload on-board memory, satellite moves in its orbit and the earth rotates around its own axis. These motions

تاریخ دریافت : ۱۳۹۵/۱۰/۱۷ تاریخ پذیرش : ۱۳۹۶/۰۶/۱۱

change the area which is visible to the satellite (satellite footprint) and this area moves to different areas of the earth. As a result, the satellite physically brings message from one station to another and it is not necessary for the destination ground station to be visible by the satellite at the same time. The maximum visibility time of a satellite in middle latitudes is 14 mins at the height of 750 kms [4]. The stations should send or receive their data in this time interval. Ground station should wait to be placed in satellite footprint; therefore a simple S&F LEO satellite system has delay in message delivery. Time delay may range from some minutes to 20 hs [5]. This delay is not acceptable for telephone but other applications such as e-mail don't require real time data transmission. A satellite, in average, has 4 orbital passages in middle latitudes. In fact, when the earth rotates, most stations will move and will be again on the satellite footprint during the day. Sun synchronous orbit is used For S&F satellite because orbital dynamics of this satellite can be predicted. An S&F satellite has useful specifications such as low price, local coverage independency from available networks, low attenuation and exceptional coverage at polar points. However, some disadvantages such as low coverage area, communications Doppler frequency shift have considerably affected attraction of S&F communications system of LEO satellite. Of course, attenuation and Doppler shift should be dominated.

Six amateur radio satellites were launched at the first time in which the Ariane structure for Auxiliary Payloads were used on January 22, 1990, and among which there were three spacecraft whose primary mission is providing store and forward and file broadcast service to the amateur radio community [6, 7]. PACSAT-1 is one of these spacecraft. PACSAT-1 includes: a VHF receiver using 1200 bps Manchester FSK or 4800 bps NRZI demodulator; a 4Ws, 70 cm transmitter band using 1200 or 4800 bps standard BPSK. UoSAT-3 is another micro satellite which carries store-and-forward Communications Experiment. There is one uplink in the 2 m band and one downlink in the 70 cm band. 9600 bps FSK modulation is used for both uplink and downlink. The UoSAT-5 also uses two uplinks in the 2 m band at 145.900 MHz and 145.975 MHz and one downlink in the 70 cm band at 435.120 MHz. 9600 bps FSK modulation is used in both uplink and downlink [7].

The design and implementation of store and forward (S&F) communication payload for Sina-1 satellite is presented in [4], which is designed based on Russian standards. 4800 bps PSK modulation and split channel reservation multiple access (SRMA) technique is used for both uplink and downlink. Error correction code is also used in this satellite to enhance the performance of communication links. Doppler shift compensation in this satellite has been implemented manually, that is, in the transmitter the Doppler shift is estimated and compensated considering satellite orbital information. Obviously, the mentioned method has not proper accuracy. Therefore it needs to increase the bandwidth of the receiver to remove the effect of inaccurate estimation of the signal, which leads to noise power increment and performance reduction.

In store-and-forward APRS mode of CubeSat-class spacecraft, the terminals use the Aloha multiple access [8].The implemented modules include AFSK modulation, Convolutional encoding and GMSK modulation for telemetry and telecommand link [9]. CUTE-1.7+APD 2 is a Japanese nanosatellite which was launched in 2008. The command uplink receiver listened in the 2m amateur radio band, and the store-and-forward message box listened at 1200 MHz with AFSK modulation at rate of 1200 baud [10]. ANUSAT is another satellite which was launched on April 20, 2009. ANUSAT carries a digital store and forwards payload which operated at VHF frequency bands. All digital FSK receiver and turbo coding for data transmission was used in this satellite [11]. TRICOM 1 is a spin stabilized satellite featuring a store and forward communication equipment and an earth imaging camera. It is to be put into an 180 kms × 1500 kms orbit with 31° inclination in 2017 [12]. CASSIOPE is a Canadian Smallsat mission whose secondary payload is a store-and-forward payload which is capable of transferring data chunks [13]. QPSK modulation and Reed Solomon (238, 206) coding is utilized for data transmission in this satellite [14].

Another type of store and forward satellites is Delay-Tolerant Networking (DTN). DTN has been defined as the concept of end-to-end store-and forward delivery, and is capable of providing communications in highly-stressed or disrupted network environments considered as 'unusual' from the perspective of the terrestrial Internet [15, 16]. The Disaster Monitoring Constellation (DMC) is another type of store and forward satellites which constructed by Surrey Satellite Technology Ltd (SSTL). DMC is a multiple-satellite Earth imaging low-Earth-orbit sensor network in which recorded image swaths are stored onboard of each satellite and later downloaded from the satellite payloads to a ground station. Store-and-forward of images with capture and later download gives each satellite the characteristics of a node in a disruption-tolerant network [15]. M2M commercial satellites that rely on microsatellites, are another type of store and forward satellite that typically deployed to provide non-real time data relay. The most well-known of the M2M commercial satellites systems is the Orbcomm satellite network that provides a global data relay satellite service for what is often called “machine to machine (M2M)” communications. One of the more common application for this type of satellite network is “supervisory control and data acquisition” (SCADA) services that are used for control of power stations, monitoring of oil, and gas pipe lines, and also managing various types of mobile fleets from trucks, buses, or rail systems to ships at the sea [17].

The aim of this paper is to present and analyze the structure of store and forward onboard communications payload. This paper is organized as follows. In Section 2, data transmission process is described. In Section 3, calculations of bit rate are given. In Section 4, simulation results are given and Section 5 presents the link budget. Section 6 describes the protocol and onboard hardware. Reviews of users’ hardware are presented in section 7. Finally, the paper is summarized with the conclusion section.

2. DATA TRANSMISSION PROCESS

2.1. Random access protocol

Random multiple access has the main advantage of allowing a common channel to be dynamically shared by a group of terminals while maintaining a low level average transmission delay. ALOHA is the simplest and first presented random access method [18]. The maximum throughput for ALOHA is 18.4 percent, which is very low. Another multiple access method is slotted ALOHA. In this method a packet can only be transmitted at the beginning of one slot. The maximum throughput for Slotted ALOHA is 36% [19]. These two methods and other prevalent random access methods have low efficiency (throughput). To solve this problem, a dynamic reservation technique which is called split-channel reservation multiple access (SRMA) is used. In SRMA, the available bandwidth was divided into two channels [20]: one of which is used for message transmission and, the second one is used to transmit control information. The control channel operates in a random-access mode such as ALOHA. When a message of one user was ready for transmission, the user’s terminal sends a request packet containing information about the address of the terminal. At the correct reception of the request packet, answer-to-request transmits back to the user’s terminal. If two or more stations transmit packets in the same time window, the packets collision takes place; therefore, the on-board receiver is not able to correctly receive the packet. If there is no reception collision and the packet is received normally, the on-board transceiver confirms the packet reception by sending the correct reception acknowledgement via downlink channel.

Fig.1. shows the state diagram of random access channel. In channel state, the packet is transmitted with probability of P_U if the channel is not busy with repeated transmission of a previously packet, and if the channel is busy the packet transmission is postponed until the next window and is performed with the probability of 1-P_U. If the channel is not busy the repeated transmission is firstly accomplished; the newly entered packet is transmitted only if there are no packets for repeated transmission. In the packet transmission state, the packet will be transmitted without collisions with the probability of P_Z and with the probability $1-P_Z$ a collision occurs in the channel. In state of the packet reception by the on-board receiver, the probability of an erroneous reception of the packet is equal to P_{PAC}. In the acknowledgement state the acknowledgement is received by the user terminal station without errors with probability of $1-P_Q$ which means a successful completion of the packet transmission process. Repeat transmission state shows that the repeated transmission of the packet is required. Repetition number checks the number of the repeated packet transmissions. If the number of repetitions exceeds the maximum possible number N_{MAX}, the packet is discarded to prevent the reduction of system throughput. In the retransmission state, the packet to be transmitted again is transmitted with the probability of P_R and postponed until the next time window with the probability of $1-P_R$.

For the access channel, there are two strategies. In the first strategy, two receivers with different frequencies are used. In other word, there are two separate receivers with different frequencies in satellite onboard; one for users’ competition and another for data transmission. Although due to the presence of two receivers, this method has higher costs, power and mass, this approach can be easily managed. In the second strategy, only one receiver is available on onboard and users can compete in a fraction of time of satellite visibility and the data is sent at the remaining visibility time [21]. In the S&F satellite, the second method which contains one receiver is selected.

In S&F communications systems, the number of users has a reverse relationship with serving time.

Limiting factor for the number of users is short time of channel access which is considerable with the increase in the number of users. Another limiting factor is the memory size and the required time of sending satellite control data to the users. The number of users depends on other parameters such as channel request massage length, time interval between initial data sending and its repeated forwarding, propagation delay and processing time. Therefore, the number of simultaneous users decreases. Based on our experience the number of simultaneous users in a scenario with bit rate of 4.8Kbps and random access time of 5 ms is about 40 users.

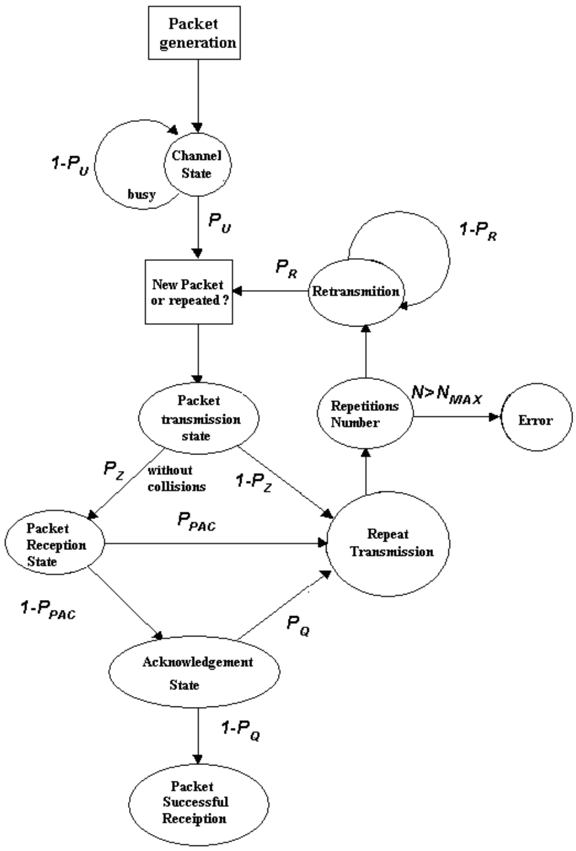

Fig.1. Onboard random access process

2.2. Modulations techniques

Selection of appropriate modulation and error detection or correction techniques helps the communication system designer to mitigate the effects of a noisy and faded transmission channel [22]-[24]. Microsatellites have limited accessible energy for downlink transmission [4]; therefore, the modulation technique should effectively use this limited power. Nonlinear amplifiers are desirable in microsatellites due to their efficiency. In a satellite system due to the fading and nonlinear power amplifiers, constant envelope modulation such as FSK, PSK and QPSK is used. FSK also has cheaper receiver compared with BPSK. BPSK should be received by a linear receiver and demodulated with a heavy demodulator. In comparison, FSK can be demodulated with a simple noncoherent receiver. The consequence of this simplicity is 4 dB reductions in performance. Another important factor in an on board satellite is hardware complexity. Implementation complexity of different modulation methods is shown in Fig. 2. Considering the issues mentioned above, non-coherent FSK was used in on-board receiver and, since its transmitter was on the ground, transmitted power could be increased to enhance the performance. The satellite transmitter also used BPSK because its modulator is simple and complexity of demodulator was transferred to the user terminal, in which there was possibility of repairing and maintenance.

In order to increase access time to the satellite and reduce transmission delay, it should be possible to communicate in low elevation angle. By calculating link budget in section 5 and considering the maximum range in elevation angle of 5°, it is observed that satellite transmitted power and transmitted power of the users' terminal should be about 5.

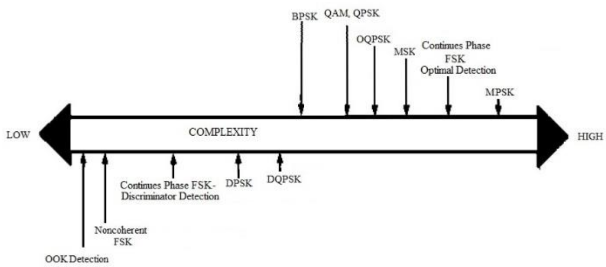

Fig.2. Complexity of different modulation methods

2.3. Coding strategy

Error detection technique, i.e. Automatic Repeat Request (ARQ) pocket communications, is used in this satellite. In ARQ system, a code with good ability of error detection has been used. There are different strategies for ARQ; including Stop & Wait (SW-ARQ), Selective Repeat (SR-ARQ) and Go-Back-N (GBN-ARQ) [25, 26]. Two ARQ strategies based on GBN-ARQ and SR-ARQ are used in S&F satellites.

Systematic Reed-Solomon code is utilized in this satellite. For a systematic block code the dataword usually appears at the beginning of the codeword. Implemented detection process is as follow: at the receiver, incoming codeword was separated into received data bits and received parity bits then parity bits are Calculated based on received data bits and polynomial generator. After that this calculated parity bits are compared with received parity bits and error detection occurs if mismatch observed.

Without considering visibility time, efficiency of these techniques is as follows [26]

$$\eta_{GBN} = \frac{1}{T_{GBN}}\left(\frac{k}{n}\right) = \frac{P}{P+(1-P)N}\left(\frac{k}{n}\right) \quad (1)$$

$$\eta_{SR} = \frac{1}{T_{SR}}\left(\frac{k}{n}\right) = \left(\frac{k}{n}\right)P \quad (2)$$

where k/n is the code rate of (n,k) code, P is the probability that a received vector contains no error and $N = R*t$ where R is bit rate and t is round trip time. For a channel with error probability of p, the following formula can be written:

$$P_c = (1-p)^n \quad (3)$$

where p is the channel bit error rate.

2.4. Doppler shift and Doppler compensation

Doppler frequency shift is one of the most challenging problems in data transmission between ground station and non-GSO satellite systems. This time varying phenomenon is caused by the line of sight (LOS) component of the relative velocity vector evolving from the rapid movement of the satellite in its orbit relative to the ground transceiver due to the Earth's rotation [27]. The Doppler frequency shift for a LEO satellite in circular orbit, altitude of 750 km, downlink frequency of 450 MHz, varied from -9 KHz to +9 KHz. Doppler Shift should be considered at the link budget calculation unless the Doppler frequency shift is compensated. In this case the total bandwidth is $2f_{d\max}+w$, in which w is transmitted signal bandwidth. Lower frequencies are more useful than higher frequencies due to lower Doppler shifts.

In both uplink and downlink, the transmitted signal should be located in receiver bandwidth for demodulation. Therefore, Doppler frequency Shift should be compensated. One method for Doppler compensation is to use broadband receiver. Receiver with high bandwidth is not used in LEO satellites; this is due to the fact that by increasing the bandwidth, the noise power increases and as a result the performance degrades.

Therefore, only one of, the two satellites or ground station should compensate the Doppler frequency shift. Some satellites use automatic frequency control (AFC) in uplink receiver to predict the Doppler frequency shift. Nevertheless, AFC degrades the modulation performance, and therefore, it is preferable to estimate the Doppler frequency shift in ground station by using AFC in satellite onboard. Ground station knows its own position and satellite coordination and can estimate the Doppler frequency shift to compensate it. It is notable that, the error variance of this method is considerable.

In an advanced satellite onboard processor, Doppler frequency shift can be extracted by obtaining FFT and specifying its peak in FSK modulation. In case of obtaining FFT, two peaks appear in $f_1 + doppler\ shif$ and $f_2 + doppler\ shif$ where f_1 and f_2 are frequency of the transmitted pulses for zero and one data respectively. Therefore, Doppler Shift can be extracted and compensated in satellite onboard. Block diagram of this method is shown in Fig. 3. It can be seen that output signals of IF Sampling block is given directly to FFT block and the Doppler frequency shift is calculated and then the frequency shift of received signal frequency is compensated by a digital mixer.

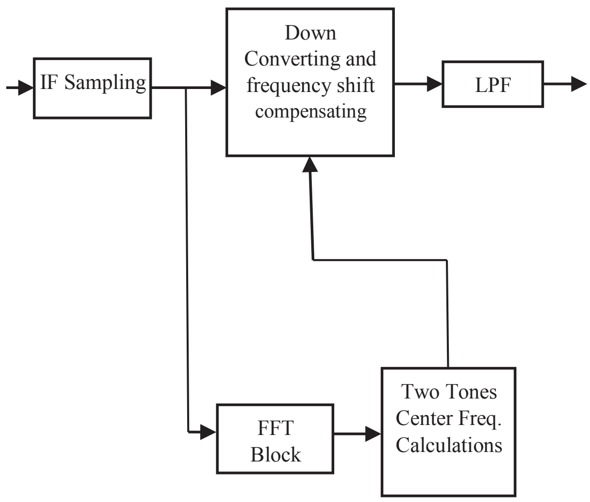

Fig.3. Calculation of Doppler frequency with FFT method in FSK modulation and its compensation

3. CALCULATION OF BIT RATE AND REQUIRED MEMORY SIZE

As mentioned, the store and forward payload is a full duplex communication link with short and periodic access time dedicated by orbital visibility. In S&F payload, communication is non-real time; all user data acquired on the uplink must be stored

onboard before the scheduled downlink. The data may have to be stored for a number of orbits.
Furthermore, Error detection and correction (EDAC) is used to protect the data from corruption due to SEUs in the memories. This means that the effective capacity available for used data is reduced by the amount of required parity data.

In sun synchronous orbit, Polar Regions have the highest coverage and radio coverage is reduced in lower latitude and reaches the minimum value in equator. The access time of an equator point is lower than middle latitude. Commercial satellite software Satellite Tool Kit (STK) (www.STK.com) is used in this section to calculate the satellite visibility time.

In Fig. 4, mean visibility time of satellite is shown in different latitudes and altitudes. Obviously, a satellite in the higher altitude and latitude has more pass number during a day. For example, satellite is visible at pole in all satellite passes and there are 6 visible pass in height of 800 km and latitude of 35°. Fig. 5 shows the daily mean visibility time in different altitudes and latitudes. With these descriptions, when the satellite visibility in ground station is 14 mins and the access time of each user is one minute, at most 14 users can compete with each other. When the transmission bit rate is 4.8 Kb/s, protocol header is 20% and the header of ARQ method is 20%, effective bit rate is 0.8*0.8*4800=3072 b/s. For the data transmission duration time (not control data) of 0.8 min (competition time of users is considered 12 s which may be much less than 12 s), the transmitted information within 48 sec would be equal to $48\times(3072/8)=18.432\,Kbytes$. A satellite in altitude 700Km has four daily passes in Tehran with a visibility time about 14 min. When one user has access to the satellite in the total time of visibility (14 minutes), the maximum data will be transferred to the satellite. The maximum transferred data for the four passes in Tehran is $(4\times48+4\times13\times60)\times(3072/8)=1.213\,Mbytes$. By considering a Hamming (12, 8) code as EDAC, the required memory size for this data is $1.213\,Mbyte\times\frac{12}{8}=1.8195\,Mbytes$. When the minimum elevation angle reaches to 10°, the average visibility reduces to 12 min and average size of transferred data to the satellite would be $(4\times48+4\times11\times60)\times(3072/8)=1.037\,Mbytes$. When the number of users increases, due to the increase in time of competition, transferred data volume reduces. Considering the effective bit rate of 3072 bits/s, the required time for storing 8 Mbyte memory, with permanent visibility (considering EDAC), is $(8\times1024\times1024\times8)/(3072*3600)*\frac{8}{12}=4.05h$. Fig. 5 shows that the maximum daily visibility time is less than 242 min which is less than 4.05 h. In order to store the acquired user data, we have utilized a 32 Mbyte memory.

The required memory size for high bitrate scenarios can be calculated as mentioned. The maximum transferred data with 3 Mbps data rate and four passes in Tehran is $(4\times48+4\times13\times60)\times(0.8*0.8*3Mbps/8)=794.88\,Mbytes$. Therefore, this payload can be used as an internal reservation for telemetry and telecommand transceivers and other payload transceivers such as imaging payload. To store the data acquired in high bitrate scenario, the store and forward payload uses a 16-Gigabyte flash memory.

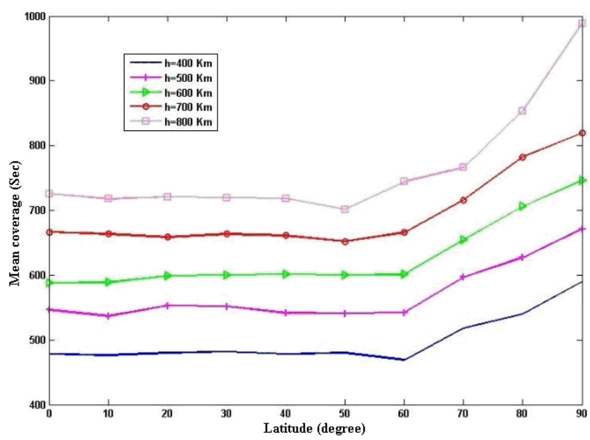

Fig. 4. Mean visibility time of one satellite pass in different latitudes and altitudes

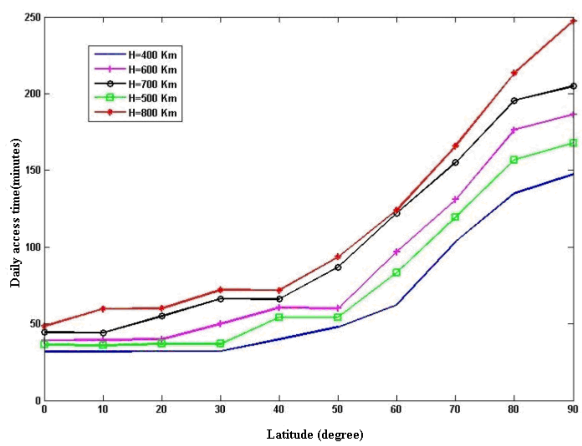

Fig. 5. Mean daily visibility time of satellite in different latitudes and altitudes

4. SIMULATION RESULTS

In this section simulation results are presented. Simulations are done using MATLAB software.

First, the performance of different multiple accessing methods simulated. Efficiency of different random multiple access methods is shown in Fig. 6. It is seen that in the region in which the ratio of random channel request frame length to the forwarded message frame length is lower, better efficiency is obtained. In other words, by reducing the random access packet length, we can reduce the chance of packet collision. It is also observed that in the low ratios of random channel request frame length, the performance of slotted-ALOHA SRMA and ALOHA SRMA schemes is the same. In our designed system, the 18-byte packet size is chosen for random access message. In Figs. 7 and 8, effect of increment in the number of users is illustrated. It is observed that when the number of users increases, the efficiency considerably reduces. On the other hand, when the random access time, which is also the competition time, boosts, the efficiency augments too. To state the matter differently, as the number of users increases, by virtue of increasing the random access time, throughput can be maintained high. It can also be observed that in a constant random access time as the number of users increases, throughput can be maintained high by increasing bit rate.

As mentioned in the previous sections, GBN-ARQ and SR-ARQ are used in S&F satellites. In Fig. 9, the efficiency of the above two strategies is illustrated; the scenario is for Reed-Solomon (255, 233) code, bit rate of 4.8 Kbps, the minimum delay of sending and receiving about 5 ms, satellite altitude of 750 km and N equal to 24. It can be observed that the bit error rate is less than 10^{-6} for efficiencies more than 80%. Naturally, SR-ARQ strategy should be selected to have higher efficiency in lower errors. In the S&F satellite, this strategy has been used.

Finally, we have simulated the standard deviation rate of estimation error of FFT method (Fig. 10). Simulation results shows that in a maximum frequency Doppler shift of 10 kHz and received SNR of -10dB, using a 4096-point FFT in $\pm 20KHz$ interval, standard deviation of estimation error would be less than 2.5 percent of the Doppler frequency. It can be also observed, the maximum error is less than 1 kHz and the error standard deviation is equal to 175 HZ. Standard deviation of error would reach below 1%, if FFT operations are repeated several times and the results are averaged.

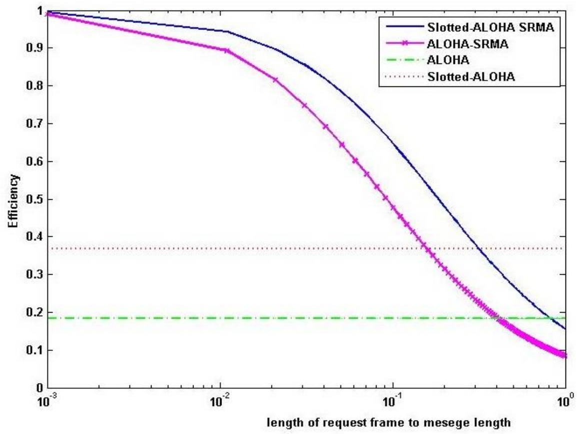

Fig.6. Efficiency of random access methods in terms of ratio of request frame length to the forwarded message packet

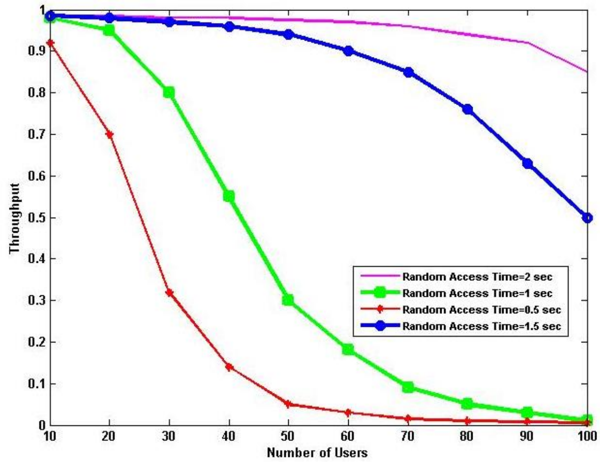

Fig.7. Simulation of SRMA throughput in terms of the number of users in bit rate of 4.8 kbps with request signal length of 18 bytes and 4.5 kilobytes data

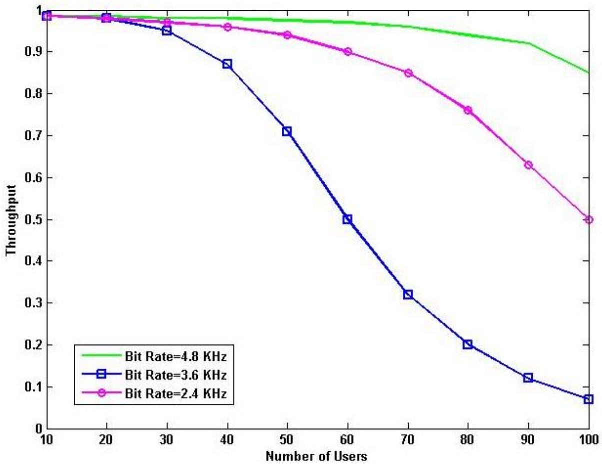

Fig.8. Simulation of SRMA throughput in terms of the number of users in random access time of 2 seconds with request signal length of 18 bytes and 4.5 kilobytes data

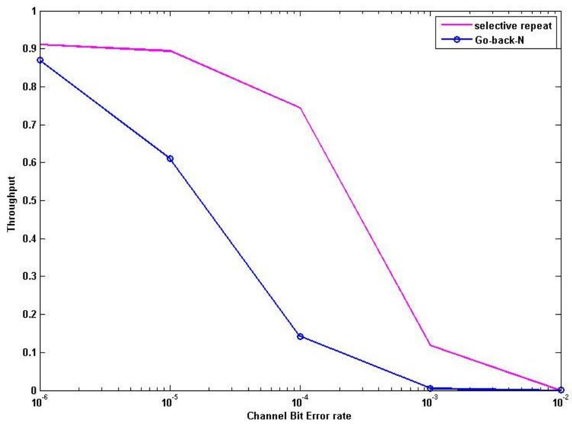

Fig.9. Efficiency of ARQ strategy in S&F payload in bit rate of 4.8 Kbps and altitude of 750 km

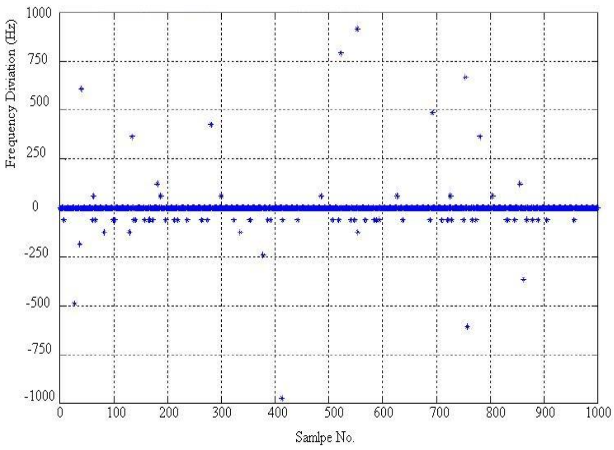

Fig. 10. Standard deviation rate of estimation error of FFT method

5. LINK BUDGET ANALYSIS

Link budget shall be prepared by the spacecraft project responsible for the correct modeling of all aspects of the links between spacecraft and Earth stations. The link budget provides the values of transmitter power and antenna gains for the various store and forward subsystems. It is, therefore one of the key items in the satellite system design and contains many characteristics of the overall system performance. At VHF/UHF frequencies the antennas, receivers and transmitters for both the ground and the space parts, are readily available and inexpensive, hence, these frequencies are used in store and forward payload system [28].

In order to ensure acceptable communication conditions with small angles of elevation, the terminal station antenna is to have maximum gain in the horizontal plane and its polar pattern is to be symmetrical relative to the vertical plane. The satellite onboard linear and circular polarization antennas are used at 145 MHz and 435MHz frequency bands, respectively. Polarization losses occur due to mismatched polarization of the on-board transceiver antenna and the terminal station one; to the other reason for such losses is the rotation of the wave polarization plane when passing the ionosphere, this phenomenon is known as Faraday effect. It is possible to reduce this loss by using a circular polarization antenna.

The link budget analyses of store and forward payload are listed in table 1. It is notable that the Faraday rotation is inversely proportional to the square of the frequency and as a result, a radio wave with high frequency will have very little polarization rotation.

Design of a satellite being able to collect and forward huge data volumes is similar to this paper but their required power, Frequency, transmitted and received Antenna gain, bit rate and required bandwidth will increased. Link budget calculation for a typical high data rate scenario is shown in table 1. Generally, high gain is achieved through using large antennas with narrow beam widths at the user terminals. Furthermore, in order to get a better performance, fully tracking antennas at the ground stations are required.

Fundamental Parameters	Uplink	Down-link	High data rate
Frequency (MHz)	145	435	1700
Transmit Power (Watts)	5	5	5
Transmit Line Loss (dB)	1	1	1
Transmit Antenna Gain (dBi)	1.8	2	3
Bit Rate (kbps)	4.8	4.8	3000
Range (km)	2300	2300	2300
Polarization Loss (dB)	4.8	4.8	0.2
Atmospheric Fading Margin (dB)	0.5	0.5	1
Multipath Fading Margin (dB)	5	5	2.5
Receive Antenna Gain (dB)	5.5	5.5	34
Received Line Implementation Loss (dB)	1	1	1
Receive Bandwidth (kHz) = 1.2*Bit Rate	10.8	10.8	3600

Receive Noise Figure (dB)	4	2	2
Required Receive Signal/Noise (dB)-This is for a bit error rate of 10^{-5}.	17	10	10
Derived Parameters			
Transmit Power (dB)	7.0	7.0	7.0
Free Space Path Loss (dB)	142.9	152.4	164.3
Receiver Noise Floor=kTB (dB)	-159.3	-164.3	-108.4
Signal Strength Analysis			
Transmit Effective Radiated Power (dB)	7.8	8.0	39.0
Propagation Losses (dB)	153.2	162.7	168.0
Signal Level at Receive Antenna (dB)	-145.4	-154.8	-129.0
Signal Level at Receiver Input (dB)	-140.9	-150.3	-96.0
Received Signal/Noise (dB)	18.3	14.0	12.4
Signal/Noise Margin (dB)	1.3	4.0	2.4

Table 1. Store and forward link budget

As mentioned in the previous section, to enhance the radio link between the user station and the satellite, error detection techniques based on Reed-Solomon (255, 233) code, are used.

6. PROTOCOL AND ON-BOARD HARDWARE

The protocol aims to provide the store and forward service between different users. Users are equipped with simple terminals. These satellites provide communications links among the users who are geographically dispersed with random accessing. The effective use of a satellite depends on having a suitable protocol. To implement protocol, different parameters such as user's requirement, user's limitations, channel limitations as well as limitations of protocol implementation should be considered. Data are transferred among users in two forms; first, broadcasting, which is from one user to all users. It is also called point to multipoint (PTM) communication. Another form is transferring from one user to a special user which is called point to point (PTP) communication. Uplink channel from users to the satellite is common among all users but the downlink channel is utilized by all users in the satellite footprint. Due to the absence of point to point communication in downlink, only the desired user should decode the received message and the users' hardware and software should be designed to make this possible.

Standard protocols, such as OSI, are used for data transmission protocols. Because of the large size header in this protocol, only layers which are necessary are used in store and forward protocol. Details of each layer are hidden from lower to upper layers. The first layer is physical layer. Channel access in uplink is based on SRMA. The second layer, i.e. the data layer, is implemented as HDLC protocol and the third layer, network layer, is implemented as AX.25. Data multiplexing, error detection and ARQ method are performed in the last 2 layers. Owing to lack of a direct link for ARQ acknowledgement, ARQ messages are multiplexed with messages in downlink. Application layer is expanded as a special protocol which enables the email service capabilities and broadcast possibility. Furthermore, the protocol is enhanced as a combination of application layer and lower layers to fulfill the payload requirements.

In summary, the physical layer comprises an SRMA multiple access method, FSK modulation for uplink and BPSK modulation for downlink. Second layer is an HDLC protocol with selective repeat ARQ algorithm and third layer for PTM link is realized based on AX.25-datagram and for PTP link is realized based on AX.25-virtual circuit.

In some store-and-forward payloads such as APRS mode of CubeSat-class spacecraft, FPGA was used as store and forward processor [7]. The power consumption of FPGA is larger than that of micro controller to perform the same function. Our proposed store and forward payload uses microcontroller as the main processor of payload. The block diagram of proposed S&F payload is shown in Fig.11 and Fig. 12. The design should be such that the uplink and downlink logic blocks are independent. Also access to the memory is controlled by the bus controller and microprocessor. The downlink logic performs flagging and formatting the stored data, adding CRC, bit stuffing and then outputting the data. Bit stuffing is used to avoid confusion between possible appearances of the flag as a bit string within the frame and the actual flag indicating the end of the frame. The uplink logic receives the incoming data, performs flagging and formatting validations and CRC coding check, bit de-stuffing and storing the information in the memory. The bus controller controls the access of the uplink and downlink logics to the memory.

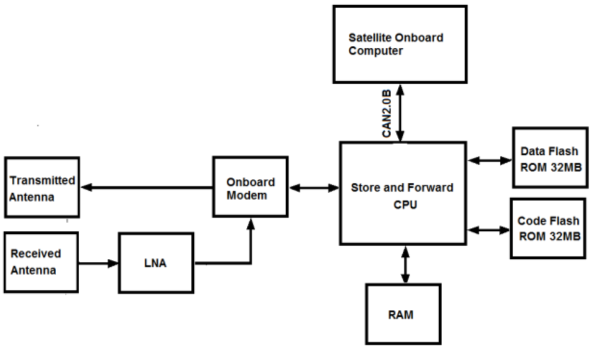

Fig. 11. Block diagram of developed S&F payload

In order to mitigate the effects of SEUs, this payload uses redundancy. If any unexpected failure occurs in the performance of one processor, the other processors without any delay take the control. The interface between S&F and onboard computer is a CAN bus whose modular, flexible, fault tolerant and robust characteristics are noticeable. CAN modules are installed in hot redundancy. Two 32 Mbyte flash memory should also be used for the data and code storage. By using flash memory, the system software can be updated by remote satellite link. Due to memory chips in space environment often suffer from single event upsets, error detection and correction (EDAC) system is essential to correct soft errors in flash memories. S&F payload uses the Hamming (12, 8) code scheme to protect its storage memories. Modem consists of receiving channels, transmitting channel and a modem controller.

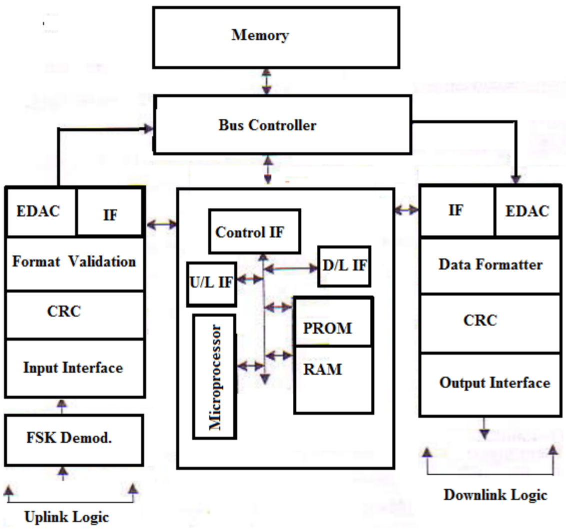

Fig. 12. Block diagram of uplink and downlink along with the microprocessor interface

The most efficient method for reliability enhancement in store and forward subsystem is hardware methods. In combination with the software methods hardware methods always ensure the required reliability with a sufficient margin. Two main methods of hardware reliability enhancement are used which include usage of special-purpose elements with high reliability and the use of reserving. The main processor of payload is a high reliable chip, but other elements such as RAM, flash ROM, and CAN bus have at least one reserve. ROM is used for storing program code (PROM) and temporary saving of received data from ground station. All data stored in flash ROM are also triplicated to increase the reliability. Reliable software means that the programs are responsible for self-testing and monitoring of all programs, also the operating system (OS) is responsible for the service and monitoring of all the executed programs. In the other word, each program ensures self-control, monitoring and control of a certain part of the hardware. As a result, all the S&F hardwares are controlled and monitored by the S&F processor. In self-testing, program tries to detect and correct the mistakes. If these actions fail, it tries to reinitialize completely or partially.

Finally, we compare our design with [4]. Utilized multiple access technique is same in both, because this method has the most efficiency between multiple access techniques. Coding, modulation techniques and protocols are different. In [4] error correction strategy is employed but in the current paper error detection methods based on ARQ is developed. BPSK is the modulation is used in [4], but, in the current paper uplink modulation utilizes incoherent FSK technique to simplify the onboard receiver structure. The downlink modulation employs PSK method which has simpler modulator. Using these two modulation procedures will be resulted in payload board simplification. In [4] a corporate standard protocol is used which is not a standard protocol however in the present paper AX.25 protocol is applied. Therefore, this payload could be received in all ground stations or users' terminals which are using this standard. Consequently, it is not required to re-design terminal for terrestrial users. In [4] Doppler shift compensation has been implemented manually, is that, in the transmitter the Doppler shift is estimated and compensated considering satellite orbital information. Obviously, the mentioned method has not proper accuracy. However, as we mentioned, in the current paper Doppler shift is estimated through FFT block and then compensated. This approach has an accuracy of about 175 Hz which is much less than previous method. Since the applied method in [4] has unreliability we need to increase bandwidth of the receiver filter to remove the effect of inaccurate estimation of the signal. Increment of bandwidth will lead to noise power increment and performance reduction. Nonetheless, in the FFT approach bandwidth increment is negligible and has not considerable effect on performance. Finally, implementation of S&F payload in [4] is performed through two diverse receivers for access channel and data channel. This will be resulted in volume, weight, and power increment. However, in current paper one receiver is used in time-sharing mode. Even though this increase software complexity but decrease hardware complexity, cost, volume, weight and consumed power.

7. USERS' TERMINAL HARDWARE

Ground station uses a multipurpose computer which creates a communication link for users to access S&F satellite network and automatically controls the ground station during the satellite pass. The multipurpose computer tasks include calculation of satellite position from ephemeris and rotating antenna tracking tools, Doppler shift calculation and correction, transferring data between satellite and users, providing the users' status and accepting the users' command. Therefore, the main components of a user terminal include antenna-feeder unit, radio modem, portable PC, and probably a GPS receiver.

Ground stations can be mobile, such as car, airplane and other vehicles, and their positions change at any time. In LEO satellites, due to the high speed of satellite, fading always occurs in urban and suburban environments. Attenuation and fading affect the received signal in mobile ground stations. In order to reduce the fading effects, some techniques such as diversity, coding techniques and the increase of satellite transmitting power can be used. Generally, in most of the satellites to subside the fading effect, time diversity is used and also data transmission is repeated several times. Time diversity is not used in the S&F satellite, because it decreases the throughput by adding extra redundancy. A diagram of the terminal station functioning cmay be found in Fig. 13.

8. CONCLUSION

In this paper, the systematical design and performance evaluation of the store and forward communication payload for a LEO satellite were described. Structure of the store and forward satellite payload was also analyzed and its required protocols were presented. The protocol was based on OSI model and included physical layers, data, network, and application layers. Physical layer was proposed based on non-coherent FSK modulation for the uplink and PSK modulation for the uplink.

Data layer included HDLC protocol and CRC coding with ARQ algorithm with selective repeat method. Network layer was also realized based on AX.25. In order to have access to the satellite, SRMA method was used which had high efficiency. Furthermore, the minimum memory size for storing transmitted data was determined. Different Doppler compensation methods were discussed and the FFT based method was simulated. Finally Specifications of the designed system were presented. Comparison of this paper and [4] show that the designed store and forward paper is more efficient than [4], because it has lower complexity, weight, volume, consumed power and better performance than [4].

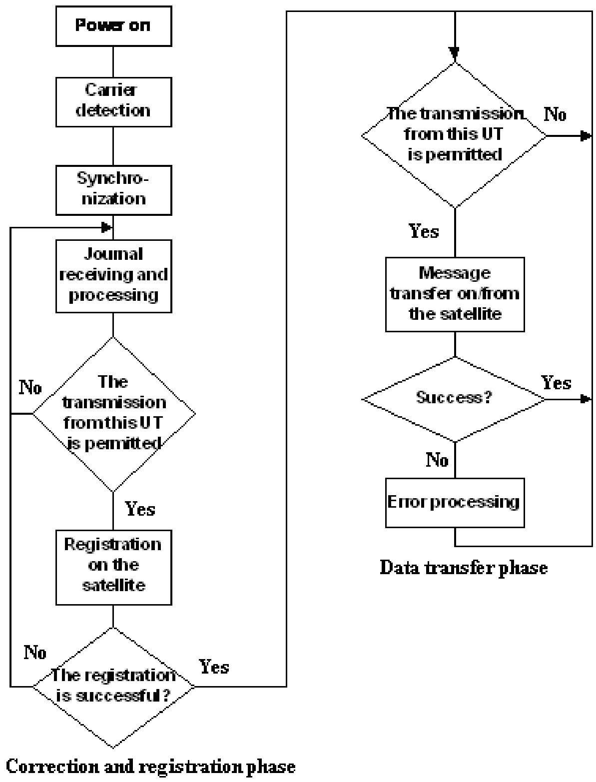

Fig. 13. Diagram of the user terminal functioning

APPENDIX A: POSSIBLE SEQUENCE FOR EVENTS IN PTM AND PTP SERVICES

A.1. PTM service

1- The user transmits its message to the satellite.

2- The received message is saved in memory.

3- Transmitting list is updated.

4- At first the title of transmitting list is sent by satellite transmitter.

5- The broadcast messages are sent based on transmitting list.

6- Stages 3 to 5 are repeated based on the time limitations.

7- Transmitting list is updated.

8- The related file of transmitted message is cleared from memory.

A.2. PTP service

1- Email message is sent in uplink from origin user to satellite.

2- Satellite stores message as a file.

3- Downlink transmitting list is updated.

4- Users receive transmitting list.

5- Destination user sends the request of downlink message.

6- Authenticity and validity of user's message are checked by satellite.

7- If the downlink request is accepted, a message will be sent to the destination user that informs the acceptance of user request.

8- Requested message is transmitted.

9- Destination user receives the message.

10- The information of transmitted message (not message) is deleted from the transmitting list.

11- If the user does not successfully receive the whole message, it will send a request for satellite to transmit a part of message in the next accessing.

12- Stages 6 to 11 are repeated until the whole message is completely received.

13- After receiving whole message, the destination user informs the satellite.

14- Satellite sends an acknowledgement packet to the user that his message has been received.

15- Transmitting list is updated.

16- The message is deleted from the satellite memory.

REFERENCES

[1] M. Antonini, A. De Luise, M. Ruggieri & D. Teotino, "Satellite data collection & forwarding systems" IEEE Aerospace and Electronic Systems Magazine, Vol. 20, pp. 25-29, Sept. 2005.

[2] N. Hamamoto, Y. Arimoto, Y. Hashimoto, T. Ide, and M. Sakasai. "High speed and global store and forward communication system using LEO satellites", Third Annual International Conference on Universal Personal Communications, San Diego, CA, 27 Sep-1 Oct 1994.

[3] N. Celandroni, ET all. , "A survey of architectures and scenarios in satellite-based wireless sensor networks: system design aspects Int. J. Satell. Commun. Network. 2013; 31:1–38.

[4] D. Abbasi-Moghadam, S. Mehdi Hoseini-Nasab Hotkani, M. Abolghasemi, "Store and Forward Communication Payload Design For Leo Satellite Systems", Majlesi Journal of Electrical Engineering, Vol. 10, No 3, pp. 7-17, 2016.

[5] M. H. Hadjitheodosiou, "Store-and-Forward Data Communications Using Small Terminals and Microsatellites", Third IEEE Symposium on Computers and Communications, Athens, Greece, 30 June-2 July 1998.

[6] R. J. Diersing, "The Development Of low-earth-Orbit Store-And-Forward Satellites in The Amateur Radio Service", Twelfth Annual International Phoenix Conference on Computers and Communications, Tempe, AZ, USA, 23-26 March 1993..

[7] R. J. Diersing, G. Jones, "Low-Earth-Orbit Store-And-Forward Satellites in the Amateur Radio Service", National Telesystems Conference, Washington DC, USA, 19-20 May 1992.

[8] A. Addaim, A. Kherras, E.B. Zantou, "DSP implementation of integrated store-and-forward APRS payload and OBDH subsystems for low-cost small satellite", Aerospace Science and Technology 12 (2008) 308–317.

[9] A. Munir, N. Febrian, A. D. Setiawan, Chairunnisa, "Signal Analysis of GMSK Modulation-based CubeSat Automatic Identification System Receiver", Proc. of 2016 3rd Int. Conf. on Information Tech., Computer, and Electrical Engineering (ICITACEE) , Semarang, Indonesia, Oct 19-21st, 2016.

[10] K. Leveque, Klofas, B., and K. Leveque. "A survey of CubeSat communication systems: 2009–2012." Proceedings of CubeSat Developers′ Workshop, San Luis Obispo, Calif, USA, September 2012.

[11] K. Thyagarajan, J.P. Gupta, P.S. Goel, K. Jayaraman," University small satellite program—ANUSAT", Acta Astronautica 56 (2005) 89 – 97

[12] TRICOM 1, http://space.skyrocket.de/doc_sdat/tricom-1.htm.

[13] M. Senez, J. Hemingway, B. Entus, A.W. Yau, G.A Enno, "Early Results of the CASCADE Technology Demonstration Payload on CASCADE," Proceedings of the AIAA/USU Conference on Small Satellites, Logan, Utah, USA, August 2-7, 2014.

[14] G. Giffin, K. Magnussen, M. Wlodyka, L. Duffield and B. Poller, J. Bravman, " Cascade: A Ka-Band Smallsat System Providing Global Movement Of Extremely Large Data Files" in Proc. IEEE MILCOM'05, Atlantic City, NJ, 17-20, Oct. 2005,pp. 550-556.

[15] W. Ivancic, W. M. Eddy, D. Stewart, L. Wood, J. Northam and C. Jackson, "Experience with Delay-Tolerant Networking from orbitz", Int. J. Satell. Commun. Network. 2010; 28:335–351.

[16] A. P. Silvaa, S. Burleighc, C. M. Hirataa, K, Obraczka, "A Survey on Congestion Control for Delay and Disruption Tolerant Networks" Elsevier Ad Hoc Networks (2014), pp. 1–17.

[17] J. N. Pelton, S. Madry, S. Camacho-Lara, Handbook of Satellite Applications, Springer-Verlag, 2013

[18] J. Luo, and A. Ephremides, "On the Throughput, Capacity, and Stability Regions of Random Multiple Access", IEEE Transactions on Information Theory, Vol. 52, No. 6, pp. 2593-2607, June 2006.

[19] L. Dai, "Toward a Coherent Theory of CSMA and Aloha", IEEE Transactions on Wireless Communications, Vol. 12, No. 7, pp. 3428-3444, July 2013.

[20] F. A. Tobagi and L. Kleinrock, " Packet Switching In Radio Channels: Part III-Polling and (Dynamic) Split-Channel Reservation Multiple Access", IEEE Transactions on Communications, Vol. Com-24, No. 8, August 1976.

[21] M. Hoseininasab, D. Abbasi-Moghadam, “Design of Communication Network in LEO Satellite”, 9th Annual CSI computer conference (CSICC’2004), Sharif University, Tehran, Iran, February 2004.

[22] Z. Gengxin, X. Zhidong, B. Dongming, S. Qian, "A Survey of Deep Space Communications", Journal of Electronics (China), Vol.28, No.2, pp. 145-153, March 2011.

[23] D. Abbasi-Moghadam, V. Tabataba Vakili, "Choice of Coding and Modulation in Space Communication Systems", First IFIP International Conference on Wireless and Optical Communication Networks (WOCN2004), Mascot, Oman, June 7-10, 2004.

[24] D. Abbasi-Moghadam, V. T. Vakily, K. Keyghobad, “Turbo codes for NONGEO satellite communications “,International Symposium On Signals, Circuits and Systems (SCS 2003),Vol. 2, Issue , 10-11 July 2003.

[25] S. Lin and D. Costello, Jr. "Automatic-Repeat-Request Error Control Schemes" IEEE Communications Magazine, Vol. 22, Issue: 12, pp. 5-12, December 1984.

[26] S. Lin, D. J. Costello, Error Control Coding, Prentice Hall, May 2004.

[27] Z. Tabakovic, "Doppler effect in non-GEO satellite propagation", Proceedings of the IEEE millennium conference on antennas and propagation, Danesy, Dorotea, AP.2000.

[28] J. Paffet, T. G. Jeans, J. Ward, "VHF-Band Interference Avoidance for Next-Generation Small Satellites," 12th AIAA/USU Conference on Small Satellites, Logan, Utah, USA, 1998.