

Power Management of LEOs under Bursty Broadband Traffic

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Abstract

Reliable operation of LEO (Low Earth Orbit) communication satellites with guaranteed Quality of Service (QOS) for real-time broadband multimedia traffic mostly depends upon its Electrical Power System. Broadband multi-media traffic is typically bursty and self-similar in nature. Integral part of the Electrical Power System is its battery. Battery supplies the power to the LEOs during the eclipse period and it also augments the solar power during the solar period, when there is not enough solar power to take care of the communication load. Varying communication traffic that a satellite is subjected to for its onboard processing and routing act as a varying load on the battery which is subjected to many thermal and power cycles during its operation in the orbit. So the traffic patterns affect the charging and discharging regime and the amount of traffic determines the Depth of Discharge level of the battery. In this paper we describe and model the battery characteristics under varying communication traffic, analyze how it affects the battery lifetime, battery mass, thus leading to satellite life-time and cost of operation respectively, and suggests few different approaches of power management strategies of the LEOs which will increase the battery life, decrease the cost of the operation, and guarantee Quality of Service of the broadband communication.

1. Introduction

A low earth orbit satellite system consists of a huge constellation of many satellites that will cover the entire globe. These satellites can have inclined or

polar orbits or a combination of the two and these orbit at altitudes ranging from 400-1000 miles. Because of the proximity to the earth's surface, low earth orbit systems promise extremely high bandwidth and low latency, and can provide local, regional, or global communication and thus will be a key player in Global Information Infrastructure (GII). The real-time communication services that can be provided by such systems in a reliable manner are broadband interactive data, voice, and image transfer between two end systems on any part of the earth. In addition these can also take part in delayed communication like one way data, image, and message transmission. Three kinds of LEOs handle different amounts of bandwidth. Little LEOs are meant for low-bandwidth applications (tens to hundreds of kbps), such as paging and include Orbcomm, big LEOs can handle paging, cellular services, and some data transmission (hundreds to thousand of kbps), examples include Globalstar, Iridium etc. Broadband LEOs (sometime called mega-LEO) operate in the Mbps range and include Teledesic, Celestri, and Skybridge²⁵. In a LEO constellation for broadband communication, satellites act more than simple relay device. These LEOs receive the packets and transmit these to other satellites through inter-satellite links or to the downstream to its coverage area. Hence a lot of processing is done in these LEOs, thus requiring a lot of power during its transmission. Thus the batteries in LEO satellites are subjected to a lot of pulse discharge, discharge gradient being more during the transmit period. It has been tested that Ni-Hydrogen cells perform very well under pulse discharge¹, power discharge being less during the receive period and more during the transmit period. LEO is subjected to

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two period during its orbital path, namely solar period, and eclipse period. Orbital period, solar period, and eclipse period for a LEO is fixed, and it depends upon the orbital parameters. When a LEO satellite is subjected to bursty communication traffic, batteries in it are subjected to a varying charging and discharging patterns during its orbital period, thus contributing to a varying charging/discharging gradients. Figure (2) shows an ideal case when there is enough solar power to the take care of communication traffic which is non-bursty, and it also charges the battery at a constant rate during the solar period. At the end of the solar period, battery is fully charged, and then during the eclipse period the battery discharges at a constant rate(optimum) and attains its DOD level within the discharge time period.

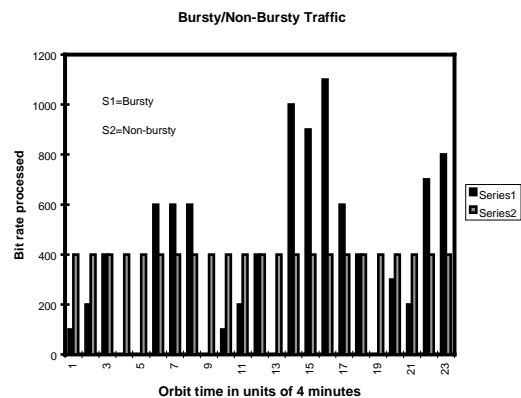
But this is far from being the case in reality, figure (3) shows a real life scenario where there is some periodic battery discharge during the solar period since solar power is not enough to take care of the bursty communication traffic, and also the battery does not charge at a constant rate, thus not being charged fully at times. During its discharge regime, many different profiles are shown whose terrain depend on the kind of traffic. We assume that amount of cumulative traffic (information) the satellite is subjected for processing over its orbital period is constant.

2. Scope

Mass/power/cost model¹⁸ relates satellite costs to the spacecraft mass and power, which in turn are dependent upon the investment and operating parameters of the satellite in the orbit. The investment cost depends upon the factors such as the number of satellites, the satellite architecture and technology, which of course involves the mass and the launching methodology. The operational cost includes the cost of maintaining the constellation integrity in terms of its reliable communication capability and orbital positioning. A proper power management strategy will reduce the mass of the battery thus reduction in launching cost, and this will also contribute to a higher battery life-time, thus contributing to a lower failing rate, and increasing the satellite life-time with lower operational cost. A reduced operation cost will reduce the cost of using these interactive services, thus benefiting the end users. Hence power management is one of the key factors in reducing the cost of the LEO satellite constellation operation which are mostly involved in broadband communication. Therefore it is crucial to study the relationship between communication traffic and battery life-time/mass for the LEO satellite.

3. Traffic Pattern

The type of traffic that may affect the communication load can be mostly characterized by mean number of cells per second L , and index of dispersion (IDI)¹⁰. IDI is defined as the variance to mean ratio of the number of cells during some time interval. IDI can thus be a measure of traffic burstiness. As an example traffic composed of constant bit rate sources has an IDI value of 0, poisson traffic has an IDI value of 1. The types of traffic that may be characterized out of these parameters (IDI and L) are, constant bit rate source, Poisson Process (PP), Batch Poisson Process(BPP), ON/OFF Process (ON-OFF), Packet Inter-arrival Process (PIP), K superposition of identical ON-OFF sources (K -ON-OFF), Double exponential Model (D-Ex), Markov Modulated Poisson Process (MMPP), Discrete Time markovian Arrival Process (DMAP). While the above are some of the traffic models which can be analyzed easily, most of the multi-media traffic in real world are statistically self-similar in nature. The critical characteristic of this self similar traffic is that there is no natural length of burst. Every time during the scales ranging from few milliseconds to minutes and hours, similar looking traffic bursts do reappear (fig.1). Such fractal behavior of real-time traffic has a serious implications for the design, control and analysis of high speed networks²⁰. Thus this fractal nature of traffic will have an effect also on the battery's charging and discharging regime in satellites, which will be difficult to predict. It would be interesting to model how battery life-time gets affected by these bursty traffic.



Fig(1) Bursty/Non-bursty traffic for the same amount of cumulative traffic

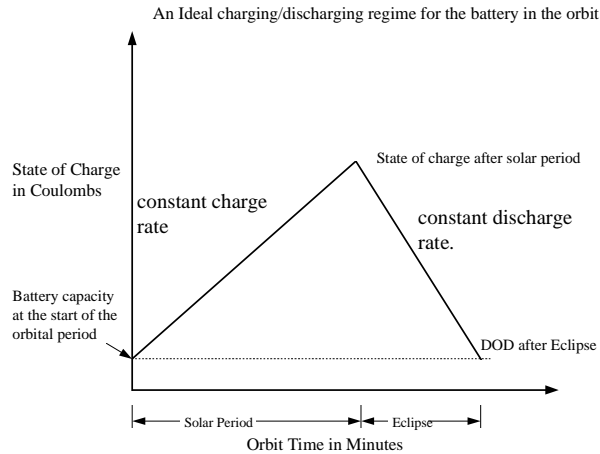


Fig.(2) Battery Characteristics under non-bursty traffic

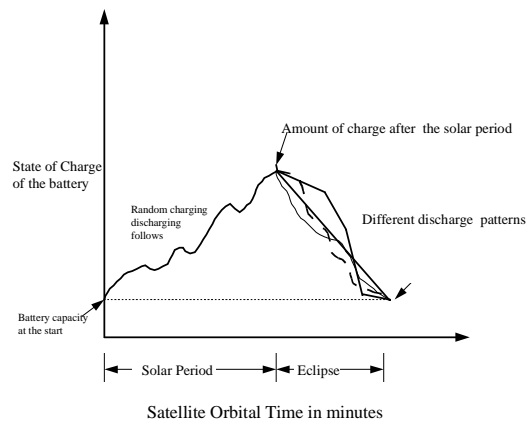


Fig.3 Battery Characteristics under Bursty Traffic

4. Battery-parameters

Battery's life-time has historically been affected by the following factors, repeated cell polarity reversal, excessive charge/discharge rate, high overcharge cell temperature, high discharge cutoff voltages. Operating temperature, discharge depth, charging and discharging regimes are the main factors that affect the battery life-time in LEO satellites. Each battery's life-time is determined by the no of cycles it can go through, before it reaches a stage where it will not have enough capacity to deliver a certain amount of power needed to drive the electronics of the satellite. Nickel Hydrogen cycle-life model is mostly based on a function of depth of discharge, varying charge rate and varying discharge rate^{5,21,17}. When a cell is fully discharged (deeply discharged) in every cycle the active materials in the electrodes are worked more causing slight degradation to occur earlier than it would have with shallow discharge. Far and away the dominant variable affecting cycle life is the depth

of discharge, which is non-linear. By decreasing the depth of discharge, the life time(no of cycles) can be significantly increased. The non-linearity of cycle life with the depth of discharge is the basis for common suggestion to oversize batteries to extend their life in cyclic application like Low Earth Orbit Satellites. Each battery is designed to work well within a certain percentage of rated capacity, if the deliverable capacity goes below a certain level then it does cease to work. The reduced capacity at increased discharge rate simply reflects a reduction in the amount of charge which is available at this increased rates. The relationship between DOD, charge/discharge rate and life cycles have been mentioned in the papers^{5, 17,21}. While DOD affects the life-time and mass of the battery, charge rate and discharge rate also have some effect on the number of cycles that a battery can withstand before its rated capacity comes down to a level where it is not well enough to serve the traffic. Figures 4 , 5, and 6 show the relationship between no of cycles to failure(Life-time) vs. charge rate, discharge rate, and depth of discharge respectively.

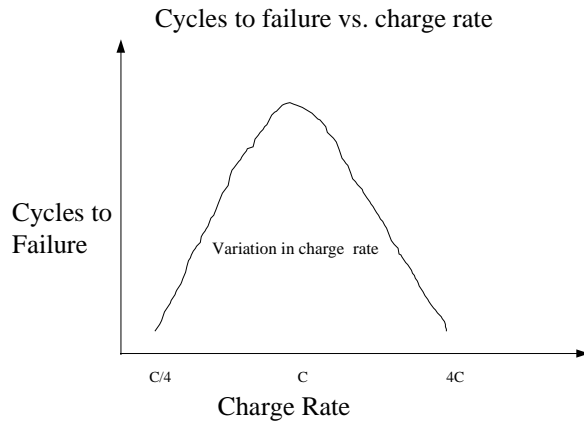


Fig 4

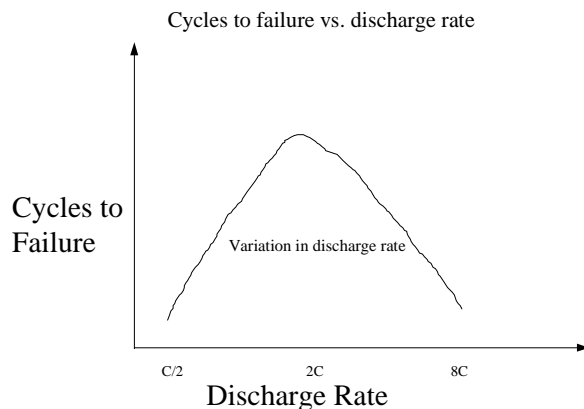


Fig. 5

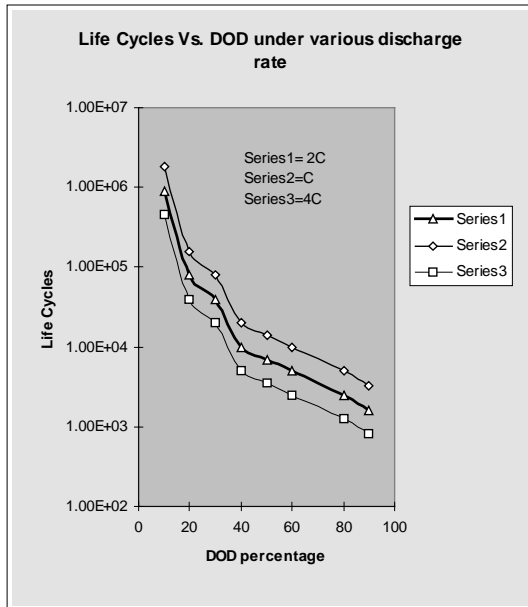


Fig.6

As a real test data from Eagle Pitcher³ Nickel Hydrogen battery, cells have accumulated over 88,000 charge/discharge cycles under an accelerated LEO regime at 15% DOD, more than 47,000 real-time LEO cycles at 30% DOD, and over 40,000 cycles under a real-time profile. As it appears batteries which are designed to operate under less DOD can last longer, but less DOD value will increase the battery mass.

4.1 Battery Mass/ DOD

Here is a small equation between capacity of the battery and DOD in an ideal situation. Assuming there is no discharge during the solar period, and the battery gets charged to its rated capacity during its charging.

T_{ecl} = Eclipse period

$$E = \text{Energy spent during eclipse} = PT_{ecl} = VIT_{ecl} = Q^2R/T = KQ^2$$

$K = R/T = \text{constant}$, Assuming R and T are constant

P = Power

V = Voltage

I = Discharge Current = Q/T

$T_{ecl} = T$

C = Capacity of the battery at the end of the charging period.

$$E = PT_{ecl} = KQ^2 = CV_d DOD n_d$$

$$C = PT_{ecl} / (n_d DOD V_d)$$

E = Energy of the battery needed for proper operation during its eclipse period. We assume here that we know

the amount of energy needed during the eclipse period which is proportional to the traffic density.

It is evident that C value is more for a bigger battery, and hence we can have a less DOD value with a higher C value or bigger battery for a fixed amount of energy, thus a higher mass will result in less DOD value thus longer life-time for the battery, and a higher DOD value will not need a bigger mass, thus increasing the battery life, so we have to find an optimum one.

If somehow because of lack charging during solar period C is less than the above factor then there will be loss of packets for lack of available energy in the battery, since value of C is determined by the state of charge(Q) at the end of solar period, which for an ideal case is the maximum state of charge a battery is designed for with some capacity loss in each cycle. So it is important to make sure that the battery does get charged to its fuller extent during its solar period, so as to provide a quality of service and reliable communication during the eclipse period. In reality this is far from the case since many times the battery does not chance to get charged fully at the end of solar period.

By design any battery should not be discharged below its DOD level, or else it will fail to operate during its discharge regime.

4.2 Battery Energy vs. satellite throughput

Most of the so called Mega-LEOs which will be used for broadband data communication will use the inter-satellite links rather than just being a bent-pipe systems, that means these will be subjected to a lot of on board processing and routing. The fundamental unit of requirement for this is energy, most of which will come from solar energy during the solar period and from the battery during the eclipse period.

Throughput of a satellite system can be defined as the rate at which the bits are actually transmitted, which are actually conditioned by the link budget⁴. Ability of the system to transfer the information depends on the network load and also on the availability of the proper battery power. Mobile Communication satellites can be treated as devices that use a finite energy supply to transfer useful information. Battery in these satellites can be treated as a device that has the means to support transmission of a fixed number of packets.

These satellites go through many power and thermal cycles because of their many rotation around the earth in a 24 hour period. A typical broadband LEO rotates around the earth in 90 minutes, with a solar period of 60 minutes and eclipse period of 30 minutes,

thus amounting to 16 cycles over a 24 hour period. Of course this number varies and it depends on the rotational speed of the satellites and its altitude. The batteries are designed to cater to a certain amount of energy over one power cycle depending upon its DOD rating. Energy gets regenerated every cycle by solar power, although not to a fuller extent. Each cycle energy available in the battery gets reduced gradually¹⁷. Although the main factor is the traffic pattern which affects the charging and discharging patterns during solar and eclipse period.

$$\begin{aligned} \text{Power} &= VI \\ \text{Energy} &= \text{Power} * \text{Time} \\ \text{Energy} &= VI * T \\ VI &= I^2 R = Q^2 R / T^2 \end{aligned}$$

Energy released from the battery $E = \text{Power} * T = Q^2 R / T$
 T is the time, for which the coulombic charges Q are drawn, R is the impedance.

Throughput of the satellite is proportional to the energy released from the battery^{4,13}. Relationship between Energy spent (Throughput) and Q (Amount of charge discharged) is shown in fig.(6).

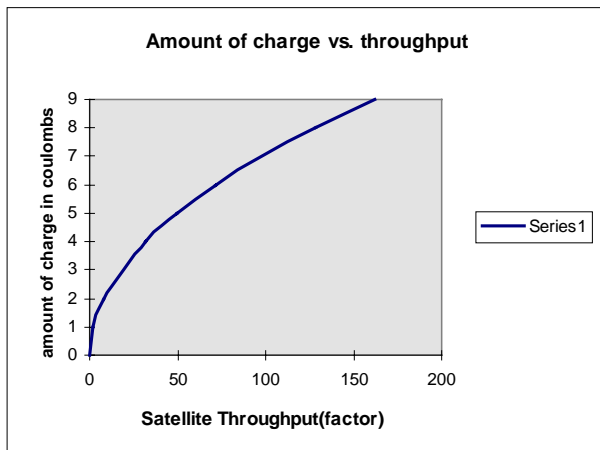


Fig6.

If T (Orbit-time) is constant and assuming R to be constant, then we have Energy is proportional to Q^2 , where Q defines the amount of charge discharged from the battery. So amount of coulombs discharged is a measure of the amount of energy released. One of the key modeling issues is characterizing the energy consumed per packet transmitted, packet is nothing but stream of bits, so energy spent is proportional to the number of bits processed in a particular period of time. Energy consumed during discharge period is completely measured by the state of charge of the battery at the end of the eclipse period. In that effect we can define the energy efficiency to be the ratio of total amount of data delivered and total energy

consumed. There are a variety of factors which will determine the energy consumed per packet or energy availability such as RF circuit design for Low power circuits, battery technology, modulation signaling, resource allocation and protocol design¹³.

The rate of transmission of the bits over a period of time will determine the state of charge of the battery and traffic pattern will determine the sequence in which the bits arrive at the satellites to be processed. So although throughput of a system determines how much energy it needs to process all its information, traffic patterns determine the charging and discharging patterns of the battery.

5. Modeling and Analysis

A proper utilization of battery is very important to have a cost effective operation for these satellites. Since there is no data obtained about how the batteries in LEOs work under bursty self-similar traffic, we present here some modeling and analysis. We do a quantitative analysis of how traffic which gives rise to variable charge and discharge rate affect the battery life-time. We also create fluid models of the battery and try to do an analytical modeling based on some facts for LEO satellites.

5.1 Quantitative Analysis

Since a battery's energy density is directly proportional to the depth of discharge of cycling, and battery lifetime decreases rapidly as DOD is increased, and since battery's charge rate and discharge rate also affect battery's cycle life, it is important to quantify the relationship between these parameters.

A simple formula for life cycles proposed by Thaller¹⁷ is $L = (1-D+0.2)/A * D$

D is the fractional DOD.

A determines the rate of capacity loss during the cycling.

L is the life cycle of the battery.

Since charge rate and discharge rate are responsible for capacity loss during the cycling^{5,6}, A is a function of charge rate and discharge rate.

Discharge rate affects the actual cell capacity because of the increasing difficulties inherent in electrolyte mass transport and electrode reactions as the current density is increased. The reduced capacity at the increased discharge rates simply reflect a reduction in the amount of charge which is available at these increased rates.

The energy represented by the capacity that is not discharged at this higher rates is not lost or dissipated. It remains in the cell where it may be discharged at lower rates. Hence discharge rate has an effect on the capacity and thus life-time as well.

Up to a certain point, deliverable capacity increases with charge rate but beyond that point, deliverable capacity decreases with the increase in charge rate, and hence charge rate has an indirect effect on the life cycles. McDermott⁵ has a nice relationship between discharge rate(charge rate) and life cycles which are shown in figures(4,5). Figure (6) shows a relationship between life cycles and DOD for various discharge rates(C, 2C, 4C), which conforms to the figure presented by McDermott.

Graph for Life cycles vs. DOD for various charge rate will be similar to the figure(6) , to avoid the redundancy it is not shown here.

A quantitative analysis of life time for variable charge rate and discharge rates can be given as follows.

As we figure out from the above value of A is determined by the charging rate and discharge rate, since it determines the rate of capacity loss.

For a LEO satellite with a particular orbit parameters , orbit period is constant say T minutes.

Total orbit period is $T = T_s + T_e = T_c + T_d$

So for one orbit cycle(battery's charge-discharge cycle)

$T_s =$ Total solar period = Constant for a particular LEO

$T_e =$ Total eclipse period = Constant for the same LEO

$T_c =$ Total charge period , it may be equal to the solar Period T_s or less, depending on if there is any discharge during the solar period.

$T_d =$ Total discharge period , it may be equal to the eclipse period or more depending on if there is any discharge during Solar period.

Depending upon the traffic, discharge rate will be different for different period of time. Say for T_{d1} minutes it discharges at a rate C_{d1} , for T_{d2} minutes it discharges at a rate C_{d2} .

So now $T_{d1} = T_d$

Since $A = F(\text{charge rate, discharge rate})$, value of A will be different for C_{d1} and C_{d2} . If the battery discharges at the rate of C_{d1} with the value of A_{d1} , for the whole eclipse period its DOD will be also different say D_1 . But since it does not discharge for the whole time,

so it will have some contribution towards the actual DOD, D.

so we define $t_{d1} = T_{d1}/T_d$, $t_{d2} = T_{d2}/T_d$ (Fraction of discharge times of the total discharge time associated with different discharge rates)

So L takes the form of $L = (1 - D_1 t_{d1} + 0.2) / (A_{d1} t_{d1} * D_1 t_{d1})$

So if we know the discharge rate and the associated length of time(which is a fraction of the total discharge time period) and the corresponding DOD value it will attain if the battery does discharge at that rate for the whole eclipse period, then we should be able to predict the life time. So by knowing the traffic pattern it will tell help us in determining the discharge pattern and hence the life time of the battery. We are assuming the charge rate to be constant during the charging cycle in the above case.

Now if we keep the discharge rate same, but vary the charge rate, then D will remain same more or less, but value of A will be different for different charge rate, and since solar period is constant too, we assume the charge period is constant for a LEO in a particular orbit

so $L = (1 - D + 0.2) / (A_{c1} s_{c1} * D)$ where s_{c1} is the fraction of the charging time of the total charging time when the charge rate is C_{c1}

So under a certain traffic condition if we have both varying charging and discharging during the orbital period , and also there will be some discharge during the solar period, then we should be able to predict the life-time of the battery by combining the above two equations.

We get $L = (1 - D_1 t_{d1} + 0.2) / (A_{d1} t_1 + A_{c1} s_1) * D_1 t_{d1}$

Where $t_1 = T_{1d}/T =$ fraction of discharge time of the whole orbit time T.

$s_1 = S_1/T =$ fraction of charge time of the whole orbit time T.

From the above equation we can determine the optimum life-time if there is a varying charging and discharging during its orbital period. figure (3) gives an example of varying charging and discharging pattern under varying traffic condition.

5.2 Analytical Models

We analyze this with a view to continuous time storage model approach. We will have three fluid models,

namely, traffic model during the whole orbital period, battery model during solar period, and battery model during eclipse. It is evident that both the battery models depend upon the traffic model parameters.

Fluid models of the battery can be done in two stages, since battery has only two stages, namely charging and discharging. Charging is done by the solar power. Charging/discharging during the solar period and discharging during the eclipse period are directly controlled by the type of traffic the LEO is subjected to. Traffic arrives on the LEO in some random fashion and then it is processed by the LEO processors.

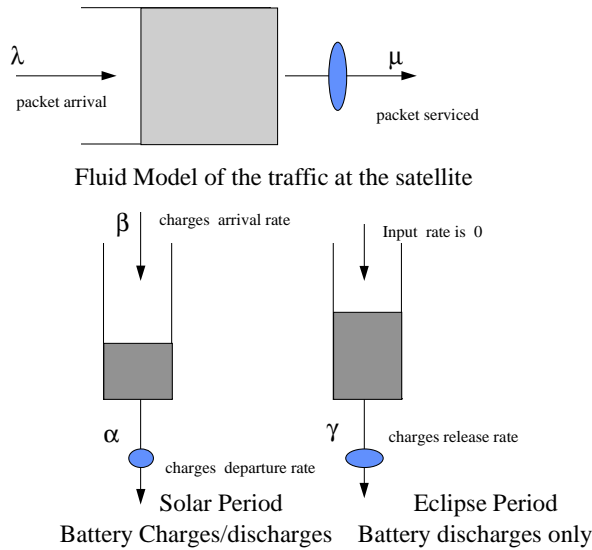


Fig. 8

5.2.1 Traffic Model

The arrival and processing packets at the satellite can be modeled as one fluid storage model, where arrival of packets(bits) can be termed as the input to the fluid model and release rate is the rate at which the processing of the packets are done. So release rate is nothing but the rate at which these packets are being serviced, as shown in fig (8). In TDMA transmission like Iridium's¹, the satellite has a time slot to receive and a time slot to transmit, and it is cyclic. So when it receives packets during its receive slot, and it transmits during its transmit slots. For simplicity we combine the transmit and receive slots as one period and hence try to figure out the parameters of the this traffic storage model. Both packet(bits) arrival and packet(bits) transmission process by the satellite need energy, transmission process being a dominant factor. Fluid release rate(μ) from the traffic storage model will affect the fluid storage rate β , discharge rate α of the

charge model of the battery, and fluid discharge rate γ of the discharge model.

5.2.1.1 Analytical parameters

λ = input rate to the storage model (arrival rate of the bits is equivalent to the fluid input)

μ = release rate from the storage model(Liquid outflow denotes departure rate of the bits)

We assume the traffic as an on/off source with some on/off probability distribution, and traffic being random or exhibiting a certain pattern during on period which depends on its nature as described in section 3. During the on period both input and release take place, and during the off period only release takes place.

For simplicity we can normalize the input and release rates. In ideal case we assume¹² during on period the bits enter at net rate $1-r$ and during an off period the bits are released at uniform rate r . Where r is the normalized release rate. But this is not the case in real life since value of r will vary according to the traffic type(bursty, poisson, MMPP, etc.) .

$Z(t)$ = amount of bits waiting the buffer to be serviced at time t .

$X(t)$ = Cumulative amount of input(bits) to the system up to the time t , ($X(t) \geq 0$) is the levy process and can be denoted as

$$X(t) = \int_0^t Y_v dv$$

Where $\{Y_v, t \geq 0\}$ is the indicator process which is 1 during the on period and 0 otherwise.

$Z(0)$ = amount of bits which were there at time $t=0$. So as per the generalized storage model it takes the

$$\text{form of } Z(t) = Z(0) + X(t) - \int_0^t r[Z(s)] ds \quad (1)$$

For simplicity we can assume $Z(0)$ to be 0. The integral above in equation(1) represents the total amount of bits processed during this time period t (orbital period).

Here of course the bit processing rate will determine the throughput of the satellite and that will also determine the charge release rate for the battery.

$Z(t)$ will denote the buffer occupancy at any particular point of time, when $Z(t)$ is 0, r becomes 0 too.

5.2.2 Solar Period Battery Model

The battery can be thought of as a reservoir and we can apply the fluid model where, charging is compared to the coulombic in-flow to the system at a particular rate β as in fig(8). During the solar period, battery is in the charging mode most of the time except for the time when solar power is not enough to take care of the communication loads and battery has to augment. If there is heavy arrival of traffic and processing rate goes up, which in turn makes the battery to discharge to meet the power requirement. Thus during that time there is no input to the storage. So unlike a regular storage model, input and release do not take place simultaneously. So as it appears traffic pattern(λ, μ) is solely responsible in determining the input rate(charge rate), β and release rate(discharge rate), α of the battery during the solar period. For a typical LEO solar period lasts for about 60 minutes.

If we look into the battery life characteristics we see that charging rate is a factor in determining the battery life to some extent. Nonlinear prediction modeling⁵ gives us a dumbell shaped curve for charging rate vs. life cycle. As it appears from the curves^{5,21} that no of life cycles(thus life-time) of the battery increases exponentially for a range $C/4 - C$, and then it decreases exponentially between $C - 4C$. Battery charging follows some periodic continuous function, that is 0 some of the time and then has some bell shape structure. The charging is 0 when it tries to augment the solar power. Because of the burstiness(self similarity of the traffic) the charging rate cannot be predicted, where as if the traffic follows a particular pattern, then it is easier to predict the charging rate, in this case charging rate is completely determined by the traffic type. Although the battery designers design the battery so as the to have the battery to be charged at some optimum charge rate(say C) so as to give the maximum life-time. The BCR(charger) in the electronics power system actually control the charging of the batteries. While the traffic is important to the second order in determining the charge rate, it is also responsible to the first degree to determine the discharge rate during the charging regime. Unlike any other battery on terrestrial applications, charging regime for a particular LEO is almost fixed, since depending upon orbit parameters, the LEOs remain under solar power for a fixed amount of time.

5.2.2.1 Model Parameters

We will denote the on period as the time when the battery is getting charged (charges accumulate), unlike previous case there will not be any release during that time. The off period will be when there will not be any

charging, but release only. In ideal case, there should not be any release during the solar period, it would be a continuous filling in process, thus the integral portion in equation (1) should be 0, but since battery does discharge to augment the solar power we can use the same equation, with t being replaced by the solar period only which is t_s and where $Z(0)$ is not 0 but some residual charge from the discharge period of the last cycle. We can also replace r by r_s which is the normalized release rate of the coulombs, during periodic discharge which depends upon the value of r .

So the equation becomes:

$$Z_{bs}(t) = Z_b(0) + X_b(t) - \int_0^{t_s} r_s[Z(s)]ds \quad (2)$$

$Z_{bs}(t)$ is the State of charge of the battery during the solar period.

Here our aim should be to regulate the input rate and release rate so that at the end of the solar period the battery should be full to its capacity. That means we have to do some traffic characterization.

5.2.3 Eclipse Period Model

Once the solar period is over, and the satellite gets into the eclipse period, it just does discharge for the whole eclipse period without getting charged at all. The same storage model can be applied during the eclipse period which is about 30 minutes for this typical case. During this time there is no input at all, and the release rate is completely controlled by the rate at which the packets are being processed, fig(8). As in the previous case period traffic patterns would determine the packets arrival rate and then some mechanism like processing power and routing strategies determine the rate at which the packets will be serviced. Burstiness of traffic gives rise to a varying discharge pattern with a varying discharge gradient over the eclipse period, thus affecting the battery life.

If we assume that the cumulative communication load that LEO will take care of during this time is constant, then for a particular kind of protocol, energy efficiency will be constant, where energy efficiency¹³ is defined as the ratio of total amount of data delivered and total energy consumed. Operative metric for measuring consumed energy will be the total number of transmitted packets, although there is some energy consumed during the receive period, which is very less compared to the transmit cycle¹.

5.2.3.1 Model Parameters

During this period there will not be any input rate, so $X(t)$ is 0, So the Equation becomes

$$Z_{bc}(t) = Z(0) - \int_0^{te} r_e[Z(s)]ds \quad (3)$$

Where t_e is the value of eclipse period here(30 minutes in our case), $Z_{bc}(t)$ is the state of charge during the eclipse period, $Z(0)$ is the state of charge at the end of the solar period which is Z_{bs} . So the equation becomes:

$$Z_{bc}(t) = Z_{bs} - \int_0^{te} r_e[Z(s)]ds \quad (4)$$

Our design should be so that $Z_{bc}(t)$ should not fall below the DOD level, similarly here also the release rate of the charges is controlled by the processing rates of the packets, where r_e is determined by the kind of traffic being processed and will be dependent upon the value of normalized r in equation 1.

Burstiness of traffic gives rise to a varying discharge pattern thus affecting the battery life. Since this discharge rate is not steady and it is completely controlled by the service rate of the packets stored and serviced in the traffic model, we can control the receive/service rate at the first model so as to regulate the release rate in the battery discharge model to an optimum value.

6. Management Issues

Key parameters in the power management issues are characterizing the energy consumed per packet transmitted, controlling the charge rate and discharge rate of the battery closer to an optimum value by some traffic characterization. State of charge of a battery at a particular point is nothing but a measure of the available energy of that battery. So energy spent during any communication directly affects the state of charge of the battery. In our discharge model we can do two things, state of charge at the end of discharge period will define the depth of discharge which will of course is a big factor in determining the battery life and the mass of the battery, while we keep the SOC at the end of discharge(DOD level) constant we can change the discharge rate so as to get a better life time, and also another management strategy will be to vary both DOD level and the discharge rate.

If the service rate gets delayed by some reason then it will affect the Quality of Service of the LEO's real time communication systems like delay, packet loss etc. Buffer management and distributed power management with feedback strategies can be thought of as the ways to regulate the communication traffic processed, so as to limit the DOD value for a particular mass of the battery and limit the charge rate and discharge rate to more or

less at an optimum value during the orbital period which will give a longer battery life.

1) In buffer management approach, we can increase the buffer size in the communication channel at the satellite and store the packets, thus reduce the release rates or release the packets at a higher rate, when we see that the discharge rate is going away from the optimum value on either side of the curve. When we control the buffer, thus regulate the service rate, we in effect control the burstiness of the traffic, and smoothen it, but it will increase the transmission delay and affect the quality of service. So we have to make a compromise between the power and the QOS to some extent while dealing with real-time communication in this approach.

2) In distributed power management approach, we can avoid the delay by controlling the receive rate, in a proactive manner with a flag set in the satellites within the same group. Satellites within the same group in a constellation are always directly connected via inter-satellite links¹⁴. It forms a robust non-hierarchical mesh or “geodesic” network that is tolerant to failure and network congestion. In a constellation like this we can take advantage of the overlapping of coverage area in getting a distributed power management approach.

Each satellite in a group (geodesic network) will keep track of the status of the other satellite's power situation (charge/discharge gradient, state of charge of the batteries etc.) by sending the signal to its neighbor, which has the same overlapping coverage area. So that those incoming packets from the overlapping region can be processed by the adjacent satellite in the group, which has not been subjected to a heavy traffic and the battery discharge gradient is below the optimum. This will help each satellite to maintain its battery's charge/discharge curve more or less at an optimum value and the battery's DOD value can be less for a specific mass of the battery. While this approach helps us attaining higher life-time without sacrificing the quality of service, it also increases the complexity by adding more intelligence into the satellites.

So each of the above approach has its own advantages and drawbacks. We need to formulate the status of the battery, find out what kind of quality of service it needs and type of communication the satellite is involved with at any particular point of time, and then we can apply a proper power management strategy appropriate to that scenario which will be different for other.

7. Summary

While this paper deals with various analysis of battery parameters with respect to its behavior under bursty broadband traffic, and takes a more theoretical approach with different models, it would be useful to analyze the effect on the battery life-time with the real data from the satellite constellation like Teledesic. More work is in progress at the time this paper is written whose results may be helpful for designing a novel LEO constellation for GII in future.

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