Doppler Based Multiple Access

Abstract

The problem of flow control for little LEO satellite communication systems is studied. In these systems the satellite functions as a "bent pipe" transponder for messaging between small terminals and a command and data acquisition (CDA) earth station. A novel scheme for averting traffic overflow on the inbound channel (from terminal to CDA), which we call "Doppler Based Multiple Access (DBMA)", is introduced. In DBMA, the CDA specifies a subset of the visibility footprint as a region of eligibility (ROE). Only terminals located in the ROE are permitted to transmit. By varying the size and location of the ROE, effective flow control on the inbound channel is achieved. The ROEs are specified in terms of parameters of the Doppler frequency-shift versus time curve observed at terminals on the outbound downlink channel (from satellite to terminal). The effectiveness and elegance of DBMA protocol are illustrated through computer simulations.

Key Words: LEO satellites, multiple access protocols, congestion avoidance, flow control, Doppler estimation.

1 Introduction

That satellite communications continues to grow in importance is hardly news. What is noteworthy is the continued evolution and refinement of distinct genres of satellite systems. At present, the great majority of circular orbit satellite systems fall into one of three classes:

1. Geostationary Earth Orbit (GEO) - the classical 24 hour orbit at zero or near zero inclination,
2. Medium Earth Orbit (MEO) - orbits significantly closer than the GEO, and yet significantly higher than the lowest possible orbits; for example, satellites with periods on the order of 6 hours,
3. Low Earth Orbit (LEO) - orbits on the order of 1000 kilometers and inclinations typically between 450 and 1050.

This paper is concerned only with a subclass of LEO satellites. This subclass is termed the "little" LEOs which are typically LEO satellites that provide a narrow class of low bandwidth aperiodic services such as messaging. Further, this little LEO subclass can be partitioned into those little LEO satellites that accomplish their mission with onboard memory in what is termed "store-and-forward" operation; and those little LEOs which function as a "bent pipe," i.e., have an onboard transponder which "turns around" or rebroadcasts incoming messages. We are concerned with this latter subclass and have encircled it in Figure 1.

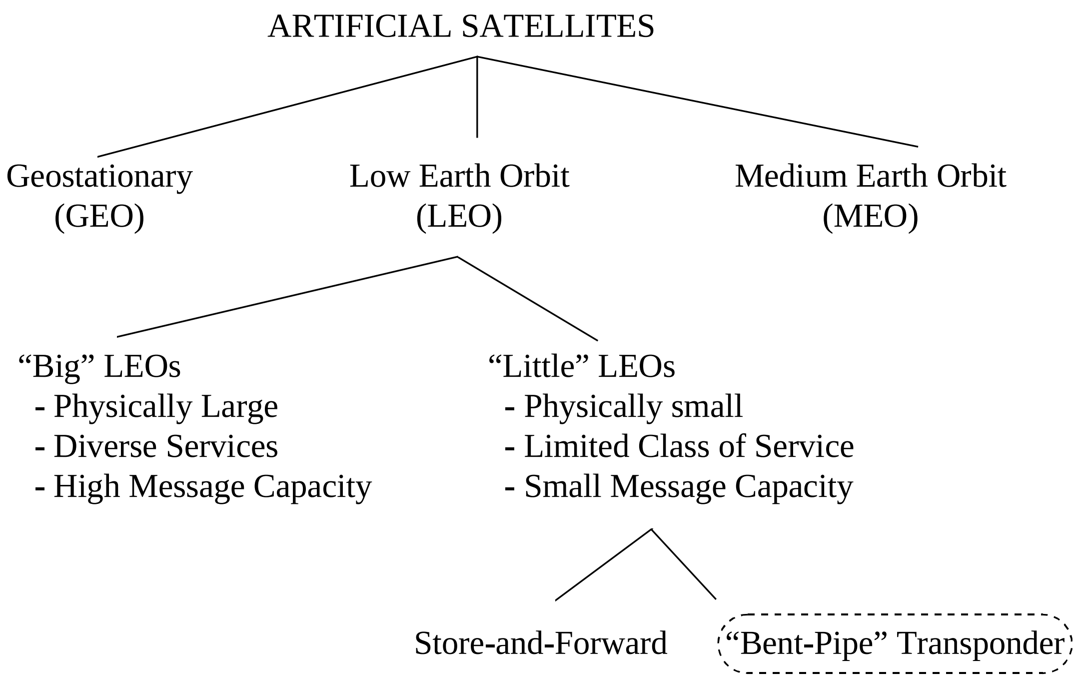

Figure 1. The main categories of circular orbit satellite systems.

Our class of interest, the transponding little LEO, holds promise for inexpensive data transport that may be of significant, if not critical, importance to certain business interests. LEOs have two highly significant advantages over GEOs. First, they are much closer to the earth and therefore the data round-trip delay is much less than that with a GEO. Second, and often more important, is that a LEO system is one of dynamic geometry as the relative geometrical relationship of the ground-based terminals and the satellite are continuously changing with time. There are many instances where a fixed or long-term non-mobile terminal will not be able to see a GEO but can expect to see a LEO on frequent basis. This is especially true in congested areas such as cities. An article by Akturan and Vogel [5] discloses that in urban Japan, the probability is greater than 50% that an earth-to-space line of sight will be blocked at an elevation below 25^0.

Exploitation of the dynamic geometry to capture its inherent advantage has always seemed to be a difficult design issue. The difficulties have been thought to reside in the necessity for a complex protocol controlling access to the transponder capacity. We investigate the intriguing idea of using Doppler information to implement flow control for LEO satellite systems. The correction for Doppler is a necessity for LEO satellite systems, as the Doppler frequency-shift is significant for these systems. Moreover, for successful reception of information in the outbound channel, terminals are required to estimate and compensate for the Doppler shift. Our new protocol requires only that the terminals keep track of the Doppler frequency-shift versus time characteristic, in addition to compensating for it.

We call the idea embodied in our concept Doppler-Based Multiple Access or DBMA. We use the Doppler frequency shift observed at terminals to control transmissions from them such that the system may function at its capacity limit at all times, i.e., serve as many terminals as possible.

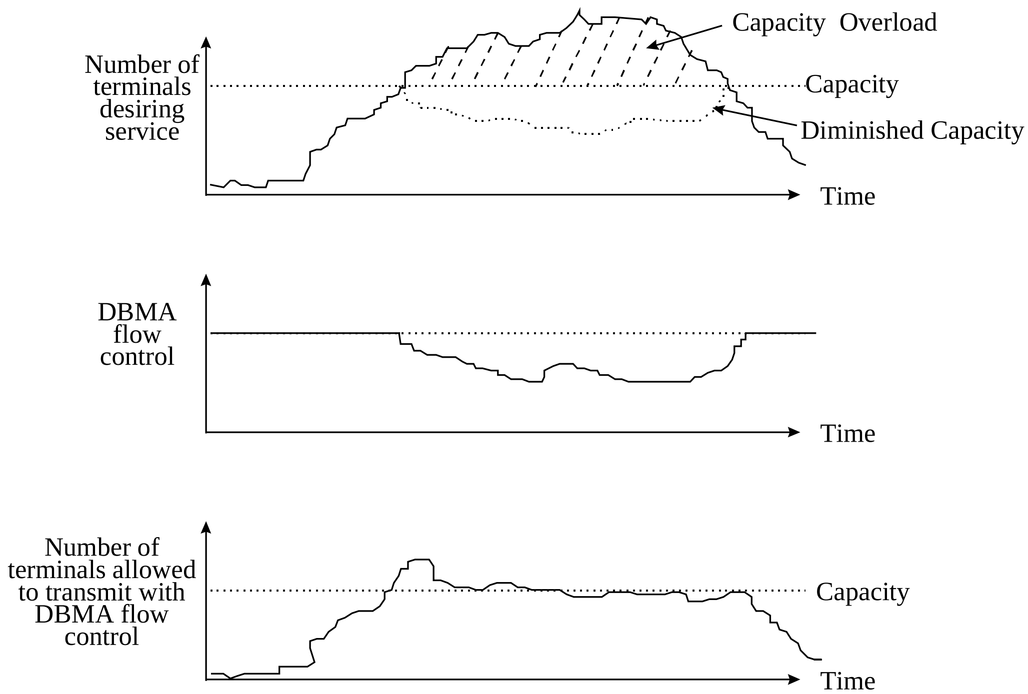

Figure 2. A sketch of the function of DBMA.

In a nutshell, DBMA functions as sketched in Figure 2. The top graph displays the number of terminals desiring to transmit as the satellite passes over the terminals. This number varies with time due to two factors: (i) the stochastic process of message arrivals at individual terminals, and (ii) the satellite's changing position with respect to the terminals. Terminals in new areas become visible to the satellite and others which were visible are no longer within the visibility footprint of the satellite. For some satellite-terminal geometries, the number of terminals desiring to transmit can be higher than the system capacity and can overload the system, as shown in Figure 2. There are two effects from such an overload. First, the terminal transmissions above capacity are surely lost, and second, and perhaps most deleterious to the system, the interference introduced by the simultaneous terminal transmissions above capacity raises background noise levels to existing users and thereby increases the probability of errors in existing terminal transmissions. This overload situation can result in a serious diminution of capacity.

The middle graph is a DBMA flow control which controls, in a new and novel way, the number of terminals communicating with the satellite. It is based upon Doppler processing at terminals and is particularly well suited to a little LEO satellites operating as a "bent-pipe" transponder.

The bottom graph shows the effect of the DBMA flow control on the number of communicating terminals. Note that it is brought to near capacity and thus provides a nearly optimal use of the satellite asset increasing the *utilized* capacity of the system.

This paper is organized as follows. In Section 2, we introduce the DBMA protocol. In Section 3, we state the processes at the CDA and terminals for the DBMA protocol. Section 4 contains results of simulation of the protocol. In Section 5, the topic of estimation of the Doppler time curve at terminals is discussed. Finally, the paper is concluded in Section 6.

2 Overview of the DBMA Protocol

DBMA is a flow control scheme for regulating traffic on the inbound channel. In DBMA, the CDA specifies a subset of the visibility footprint as a region of eligibility (ROE). Only terminals located in the ROE are permitted to transmit. By varying the size and location of the ROE, effective flow control is achieved on the inbound channel.

DBMA control is a centralized flow control scheme, i.e., the CDA determines the ROE. This is communicated to the terminals via the outbound channel. The remarkable feature of this method is that the ROE is defined solely by the characteristics of the Doppler frequency-shift versus time function, henceforth referred to as Doppler-time curve, on the outbound channel. The Doppler-time variation observed at terminals is fairly significant because of the low altitude of the satellite's orbit. The Doppler-time curve is a smooth fast varying "S-curve" due to the rapidly changing geometry between the terminal and satellite.

For illustrative purposes, we consider a configuration comprising a single satellite in a circular orbit. The CDA is located at San Francisco, and terminals are located in the continental United States. The satellite follows a circular orbit (eccentricity=0) of altitude 1000 km, and inclination 53^0. The revolution period of the satellite is 1.75 hours [9]. This orbit is fairly representative of LEO satellite systems proposed for operation [7]. The cut-off elevation angle for communication is assumed to be 10^0, i.e. a terminal can communicate with a satellite only if the elevation angle from the terminal to the satellite is greater than or equal to 10^0. In the remainder of this paper when we state that a satellite is visible to a terminal, we mean that the elevation angle from the terminal to the satellite is greater than or equal to 10^0. Hence, the visibility footprint of a satellite is the region on earth's surface where the elevation angle to the satellite is greater than or equal to 10^0.

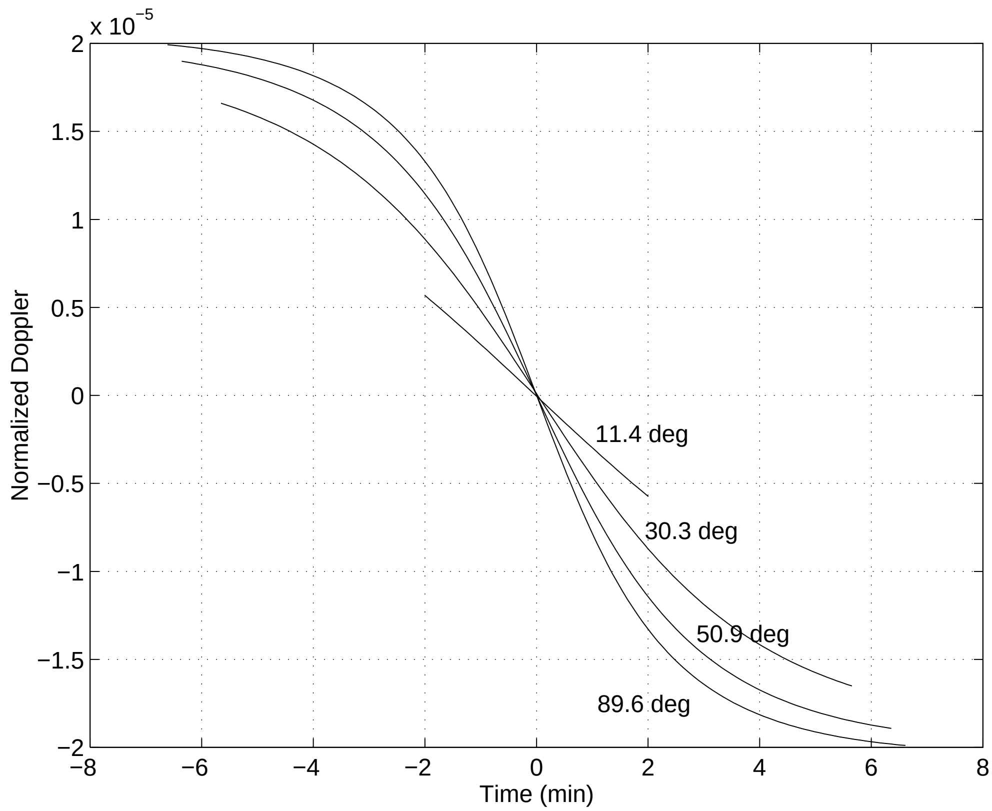

Figure 3. Doppler-time S-curve observed at terminals on the outbound downlink channel for maximum elevation angles 11.4^0, 30.3^0, 50.9^0 and 89.6^0.

The DBMA protocol utilizes the fact that the Doppler frequency at terminals exhibits a well-behaved variation with time that can be parametrized by the maximum elevation during the visibility duration of the satellite at the terminal. This S shaped variation is depicted in Figure 3 for maximum elevation angles ranging from 11.4^0 to 89.6^0. Doppler shift is captured in terms of normalized Doppler shift which is equal to (v/c), where v is the relative velocity of the satellite with respect to the terminal and c is the speed of light. The actual Doppler frequency shift observed at the terminal is $(v/c)*f$ where f is the central frequency of the outbound channel. Time is expressed relative to the zero-Doppler instant. . These curves are similar to the ones previously reported in literature [6]. For a carrier frequency of 150 MHz, the Doppler frequency exhibits noticeable variation, up to 3 kHz, over the satellite visibility time interval. This variation can be measured and tracked in the receiver frequency synchronization circuitry prior to data demodulation

A similar Doppler-time curve is observed at the satellite on the outbound uplink channel (from CDA to satellite). If the outbound uplink shift is not compensated for, the Doppler shift observed at terminals will be the cumulative effect of the shift in the outbound uplink direction and the outbound downlink direction. However, in most LEO operations, the CDA monitors and compensates for the Doppler frequency shift in the outbound uplink direction. Hence, the Doppler shift observed at a terminal is due only to the relative geometry between the terminal and the satellite. For the DBMA protocol, it is a *requirement* that the CDA compensates for the Doppler frequency shift in the outbound uplink direction.

The terminal makes a few Doppler frequency shift measurements. These measurements enable it to determine which Doppler-time curve it is observing. The terminal infers two important parameters from the Doppler-time curve which are used in the DBMA protocol. The first is the maximum elevation angle to the satellite which will be observable at the terminal: θ_{max}. The second is the estimate of the time instant of zero-Doppler: t_0. The details of the estimation process are given in Section 5.

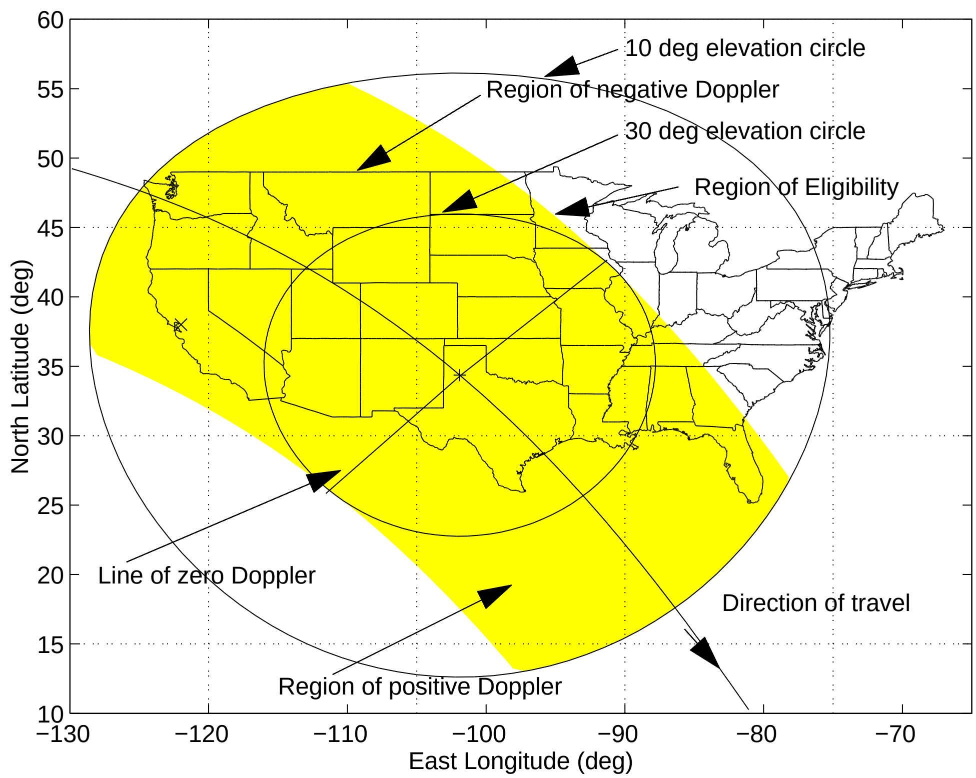

Figure 4. ROE for transmission with cut-off maximum elevation angle of 30^0.

For flow-control, the CDA describes the ROE for transmission in terms of these two parameters. Let us first consider the parameter θ_{max}. Consider Figure 4. The present location of the satellite is over the subsatellite point shown by a '+' over Texas on the ground trace. The outer circle is the locus of points on the earth's surface where the elevation angle to the satellite is 10^0. This is the circumference of the communication visibility region. For all points inside the circle, the elevation angle to the satellite is greater than 10°. The inner circle is the locus of all points on the earth where the elevation angle to the satellite is 30°. The edge of the shaded region parallel to the ground trace, is the locus of all points on the earth's surface within the 10^0 elevation angle circle where the *maximum* elevation angle to the satellite is 30°; the maximum is taken over the visibility duration of the satellite at a terminal. All points in the shaded region will observe maximum elevation angle greater than 30° at some time in their corresponding satellite visibility duration. In literature, this region is referred to as the 30° swath of the satellite [8].

All terminals in the shaded region observe one of the Doppler S-curves corresponding to maximum elevation angles between 30^0 and 90° (Figure 3). The terminals on the perpendicular to the ground trace at the subsatellite point observe zero Doppler. The satellite is at its closest approach to these terminals and these terminals observe the maximum elevation angle to the satellite at the present instant. The terminals within the 30^0 swath behind the zero Doppler line, observe negative instantaneous Doppler frequency shift. These terminals have already observed zero Doppler. Correspondingly, in Figure 3, these terminals observe Doppler on the Doppler-time curve to the right of the zero-Doppler instant. The terminals within the 30^0 swath along the direction of travel of the satellite and ahead of the zero Doppler observation line, observe positive instantaneous Doppler frequency shift. These terminals are yet to observed zero Doppler. Correspondingly, in Figure 3, these terminals are observe Doppler on the Doppler-time curve to the left of the zero-Doppler instant.

One parameter which the CDA uses in describing the ROE on the earth's surface is a cutoff maximum elevation angle $\theta_{max,c}$. Those terminals in the visibility region of the satellite which observe a maximum elevation angle greater than $\theta_{max,c}$ are permitted to transmit. If $\theta_{max,c} = 30^0$, the shaded region of Figure 4 is the ROE for transmission. The terminals in the 10° visibility region of the satellite, but outside the shaded region are not permitted to transmit.

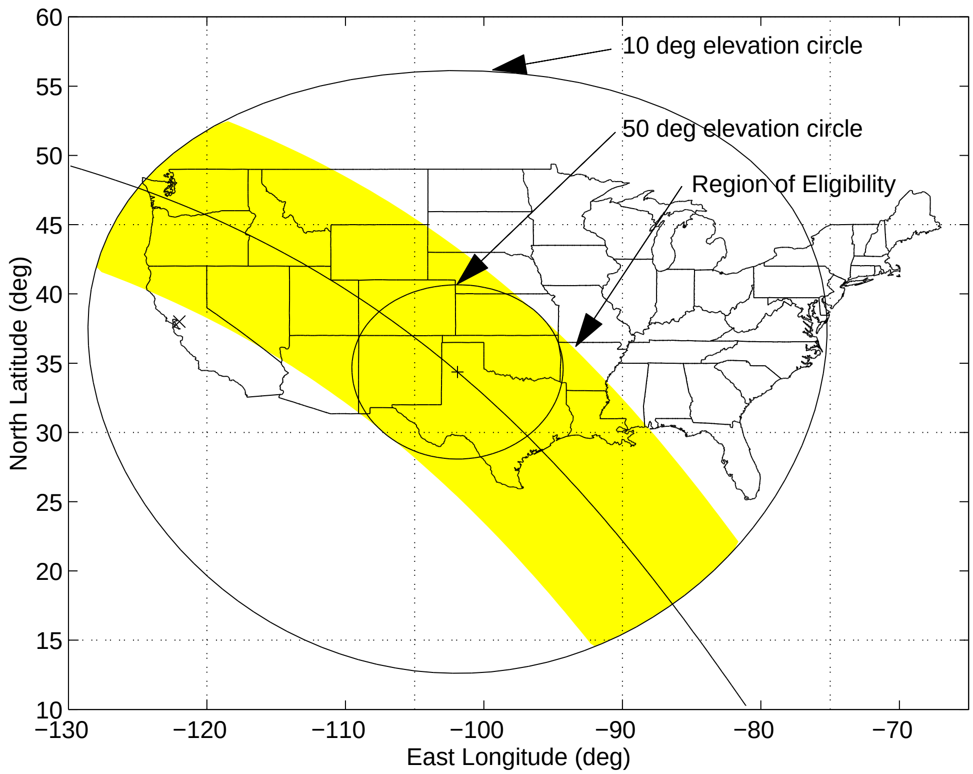

Figure 5. ROE for transmission with cut-off maximum elevation angle of 50^0.

By varying $\theta_{max,c}$ the CDA controls the contour of the ROE. Figure 5 shows the ROE for $\theta_{max,c} = 50°$. This region is narrower than that one corresponding to $\theta_{max,c} = 30°$ (Figure 4). Hence, $\theta_{max,c}$ determines the width of the ROE.

For $\theta_{max,c}$ =10°, the ROE is the entire 10° visibility circle; for $\theta_{max,c}$ = 90° the ROE is the ground trace in the 10° visibility circle.

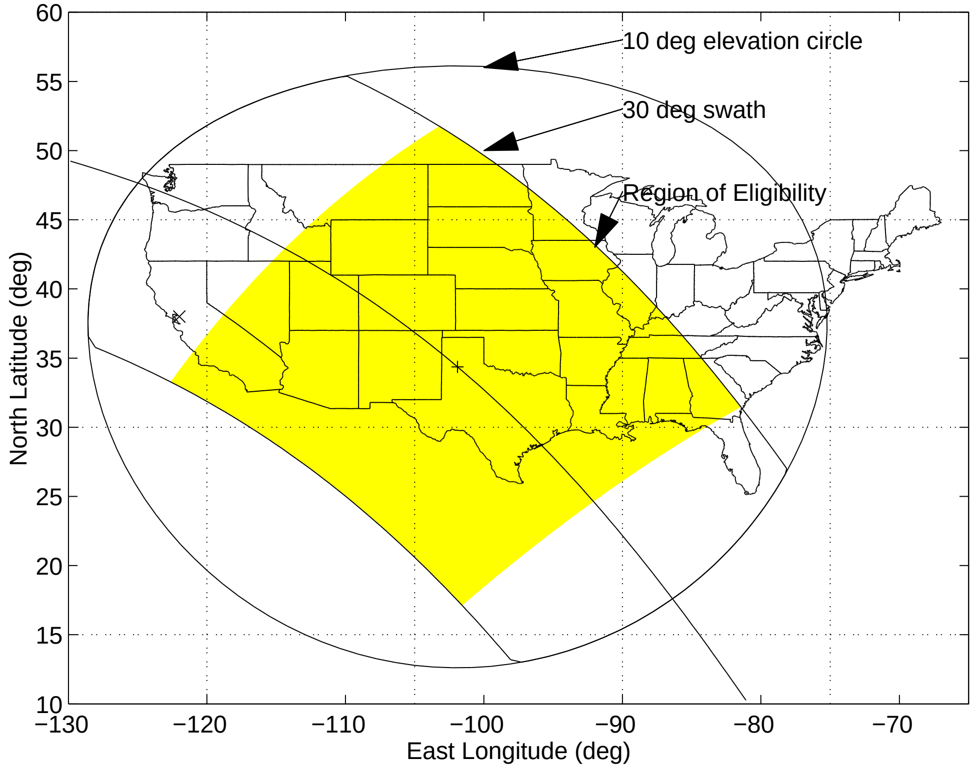

Figure 6. ROE corresponding to 8 min [-4,4] interval about the zero Doppler time and cut-off maximum elevation angle 30^0.

Another parameter the CDA uses to define the ROE is a time interval about the zero-Doppler instant on the Doppler S-curve. Let us denote this parameter by t_c. Those terminals which observe instantaneous Doppler within the time interval ($-t_c$, t_c) about the zero Doppler time t_o are eligible to transmit. The ROE corresponding to t_c = 4 min and $\theta_{max,c}$ = 30° is shown shaded in Figure 6. All terminals in the shaded region have either observed zero Doppler during the past 4 minutes or will observe zero-Doppler within the next 4 minutes.

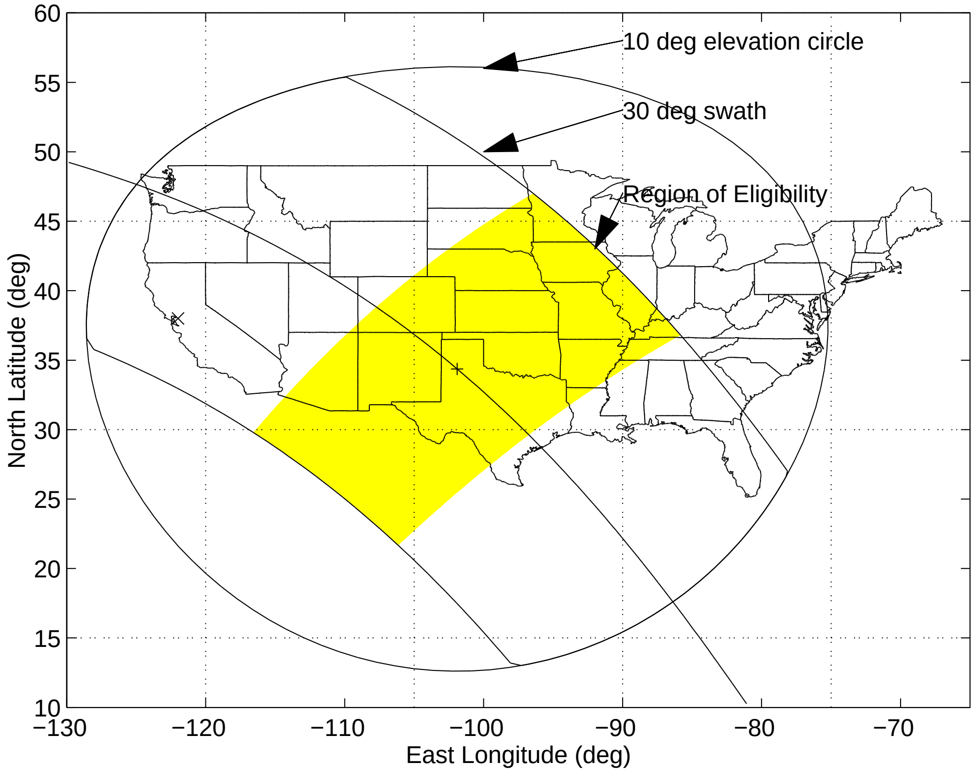

Figure 7. ROE corresponding to 4 min [-2,2] interval about the zero Doppler time and 30^0 swath.

In Figure 7, the shaded region corresponds to ROE with t_c =2 min and $\theta_{max,c}$ = 30°. The parameter t_c determines the length of the ROE. Given $\theta_{max,c}$ =30°, for t_c = 0 min, the ROE is a line perpendicular to the ground trace at the subsatellite point '+'. Terminals on this line observe zero-Doppler at this instant.

Thus, through two parameters, maximum elevation angle $\theta_{max,c}$ and time interval about zero-Doppler, t_c, DBMA controls the size of the ROE. This provides a two axis control of the ROE. By varying the size of the ROE for transmission, DBMA regulates the number of terminals which communicate to the CDA, thus regulating the load on the inbound channel.

3 DBMA Protocol Processes

The DBMA protocol processes are composed of two sub-processes: one at a terminal and one at the CDA.

3.1 At the terminal:

As a satellite comes into common view of a terminal and the CDA, the terminal determines:

1. the expected maximum elevation of the satellite to the terminal, and
2. the time to the maximum elevation of the satellite.

This information is obtained from the Doppler-time curve observed at the terminal.

The terminal monitors the CDA outbound link to determine the terminal's eligibility to transmit should it have a message waiting in the transmit queue. This eligibility defined by a message from the CDA in the outbound channel with:

1. lower bound on the maximum elevation of the satellite, and

2. limits on a time interval centered at the time of zero-Doppler.

If the terminal has a message to transmit and if it is eligible to transmit during the present satellite pass, the terminal selects a start transmission time at random within the available time window of eligibility.

3.2 At the CDA:

The CDA monitors the cumulative terminal transmission load on the inbound channel. If this load exceeds the capability of the CDA, the CDA reduces the size of ROE for transmissions and broadcasts this restriction. The CDA controls the ROE by allowing terminals to transmit only if the maximum angle of elevation falls within a tighter set of limits. The CDA also adjusts the inbound channel load by changing limits of the time window around zero-Doppler instant.

4 Simulation Results

We illustrate the effectiveness of DBMA through simulations. The simulation comprises a single satellite in a circular orbit of altitude 1000 km and orbit inclination 53^0. Terminals are modeled as point sources of traffic located in continental US. For our simulation we assumed 10,000 terminals uniformly distributed over a rectangular area between the latitudes of 30° N and 50° N and longitudes -125° E and - 75° E, which serves as an approximation of the geographical extents of continental US. Terminals communicate with the CDA through the satellite when the satellite is visible (greater than 10^0 elevation angle) to *both* the terminal and CDA.

Load on the inbound channel, in our simulation, is measured by the number of terminals that can communicate to the CDA. We have used this simple definition to introduce and illustrate the operation of DBMA flow control. As discussed previously DBMA controls traffic on the network by changing the size of the ROE for transmission. This regulates the load on the network irrespective of whether load is measured in terms of number of nodes transmitting or number of messages per unit time.

For the results provided here, we have assumed that terminals are able to exactly determine the correct Doppler-time curve they are observing. Hence, they make no errors in estimating the maximum elevation angle to the satellite and the time to zero-Doppler. Also, we have ignored the latency between the transmission of the two parameters $\theta_{\max,c}$ and t_c and its reception by terminals in the visibility footprint of the satellite.

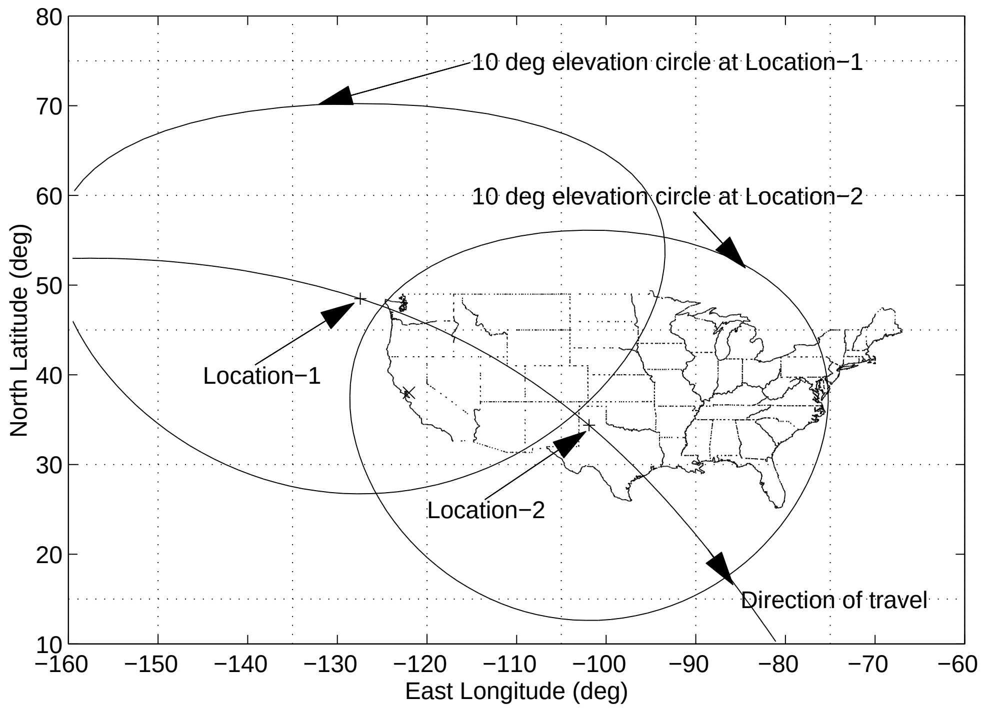

Figure 8. 10^0 visibility region of satellite for two locations of the satellite separated in time by 7.2 minutes.

To appreciate the dynamics of the load on the inbound channel as the location of satellite changes, consider Figure 8. Figure 8 shows a segment of the ground trace along with 10° visibility regions for two locations of the satellite separated in time by 7.2 minutes. These locations are marked by '+' on the ground trace. The location of the CDA is represented in the figure by an 'x' in San Francisco. The load on the channel varies dynamically as new regions on earth become visible to the satellite while other regions which were visible are no longer within the visibility footprint of the satellite. This is illustrated in Figure 9 which plots the load on the inbound channel with time for one pass of the satellite over US. Time is expressed in minutes from the start of simulations. The traffic increases from 1000 terminals to about 9000 terminals as more areas of US are covered by the 10^0 visibility footprint of the satellite. The traffic drops off to zero suddenly at the end of the pass as the satellite loses visibility to the CDA. The capacity of the system is assumed to be fixed at 6000 terminals.

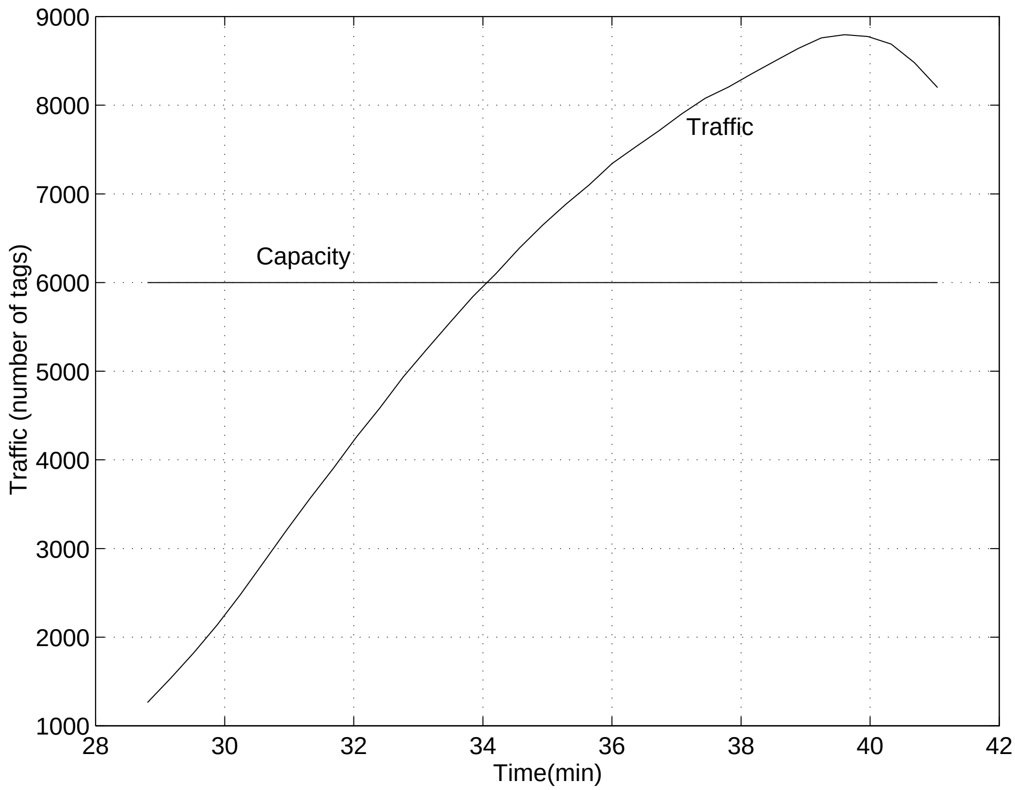

Figure 9. Traffic variation during a single pass of the satellite.

The algorithm at the CDA for determining $\theta_{max,c}$ and t_c is as follows: If traffic from ROE is greater than the capacity, (Step 1) increase $\theta_{max,c}$ by $\Delta\theta$ (=5^0), check if the traffic is below capacity, if not (Step 2) reduce t_c by Δt_c (=30 sec) and check if traffic is below capacity. Repeat steps 1 and 2 till the traffic is just below capacity. The initial condition is to let the ROE be the entire 10^0 visibility region ($\theta_{max,c}$ = 10^0 and t_c = 7 min).

Traffic is measured by counting the number of terminals within the ROE. The simulation is advanced every 21.6 seconds (4000 samples in a 24 hour day), the new location of the satellite generated and the DBMA protocol applied.

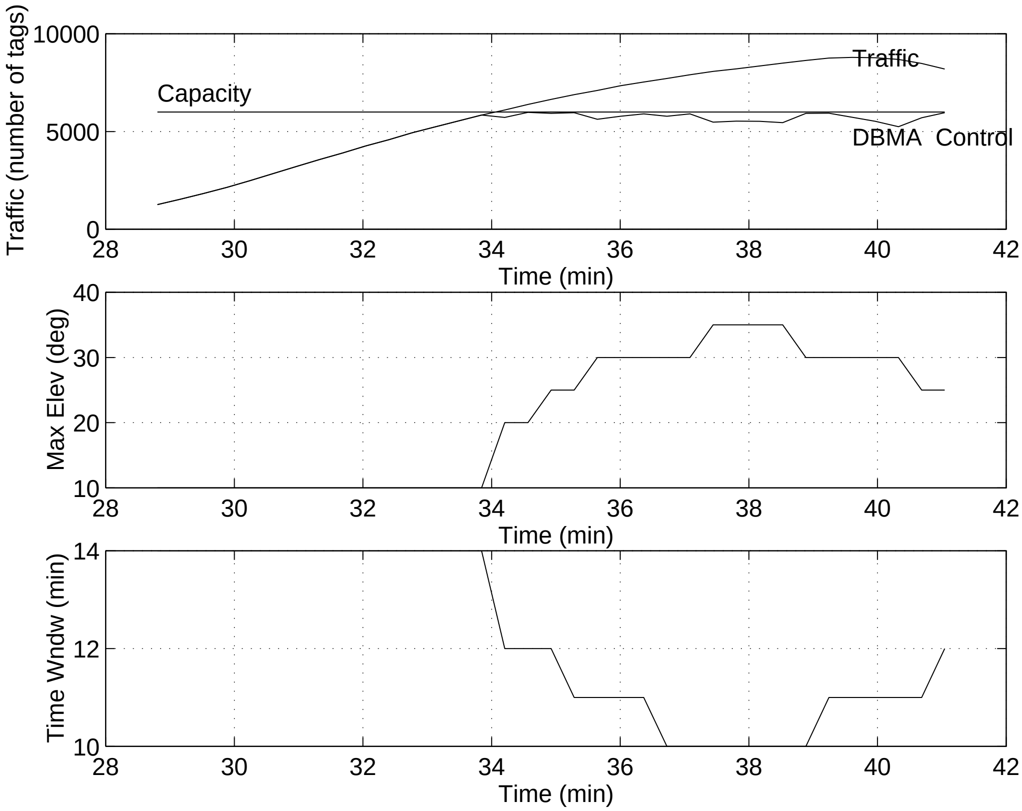

Figure 10. Result of simulation of DBMA protocol for flow control, pass A.

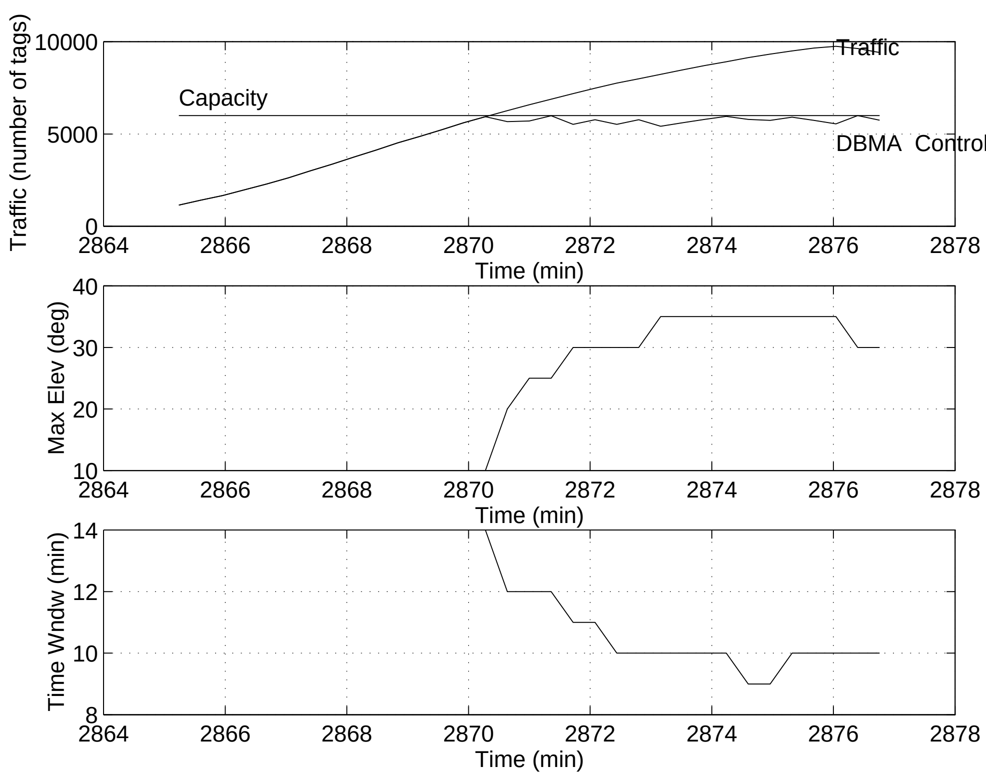

Figure 11. Result of simulation of DBMA protocol for flow control, pass B.

Figure 10 and Figure 11 show the result of DBMA protocol for two different passes of the satellite over continental US. Each figure consists of three plots. The first plot has three curves. The first curve depicts the uncontrolled traffic on the inbound channel. The second curve shows the capacity of the inbound link. The third curve is a plot of the load on the inbound channel as a result of DBMA. The second and the third plots show the time variations of the control parameters $\theta_{max,c}$ and t_c respectively.

From these two figures, we observe that the DBMA protocol is very effective in throttling the load on the inbound channel at or below capacity. When the load on the channel is below the rated capacity of the channel, all terminals in the visibility footprint are permitted to transmit, i.e., the ROE is the 10^0 visibility footprint. When traffic goes above the rated capacity, DBMA modifies the ROE to maintain the load at its rated capacity. The control algorithm at the CDA does not exhibit oscillations in the value of the two control parameters with time.

5 Doppler curve estimation

Using Doppler frequency measurements, our objective is to predict the maximum elevation angle and zero Doppler time, t_0, for the Doppler S-curve. Careful inspection of Figure 3 shows that if we consider transmission times up to t_0, the Doppler-time characteristics can be approximated by a quadratic functional dependence. We show a sample of our quadratic Doppler curve fitting results in Figure 12 for a maximum elevation angle of 39.4^0. The estimate was computed using three Doppler frequency measurements during the first 3 minutes of satellite visibility. It is noted that for small elevation angles (less than 25 degrees), the Doppler-time characteristics is linear.

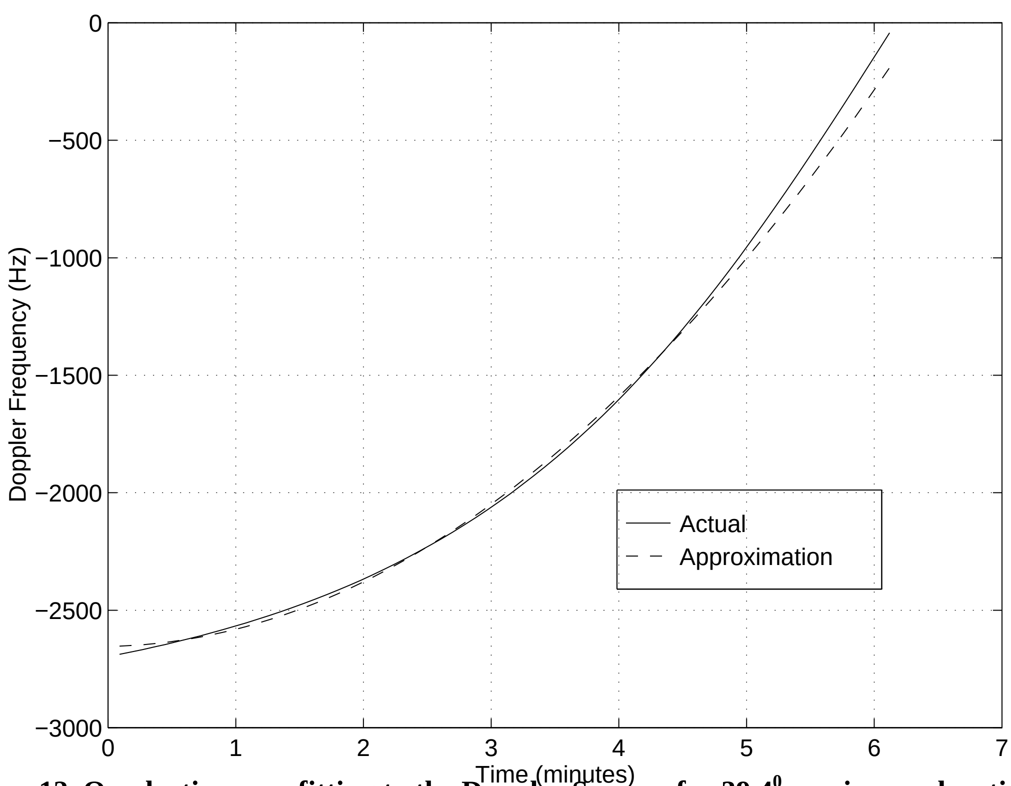

Figure 12. Quadratic curve fitting to the Doppler S-curve for 39.4^0 maximum elevation angle.

Figure 13 shows the variation of the mean square estimation error (in dB) between the actual and estimated Doppler frequency. In Figure 14, we have plotted the ideal value of t_0 together with its estimated value (using quadratic curve fitting) as a function of maximum elevation angle. It can be seen from the figures that the maximum error in estimating zero-Doppler instant is less than 1.5 minutes.

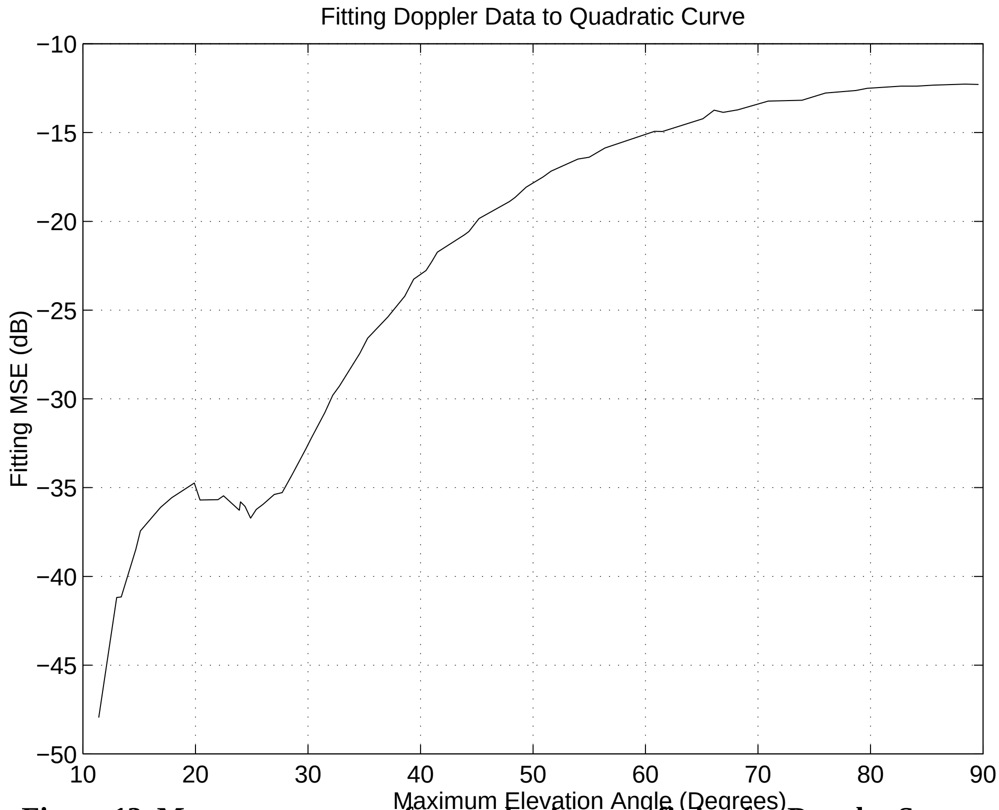

Figure 13. Mean square error for quadratic curve fitting for Doppler S-curve.

Fitting accuracy for higher maximum elevation angles can be improved by using more Doppler measurements and using a higher-order polynomial fit. Another promising means for improving fitting accuracy, is to use Doppler rate me[illegible] Doppler rate of change decre[illegible] at t_0.

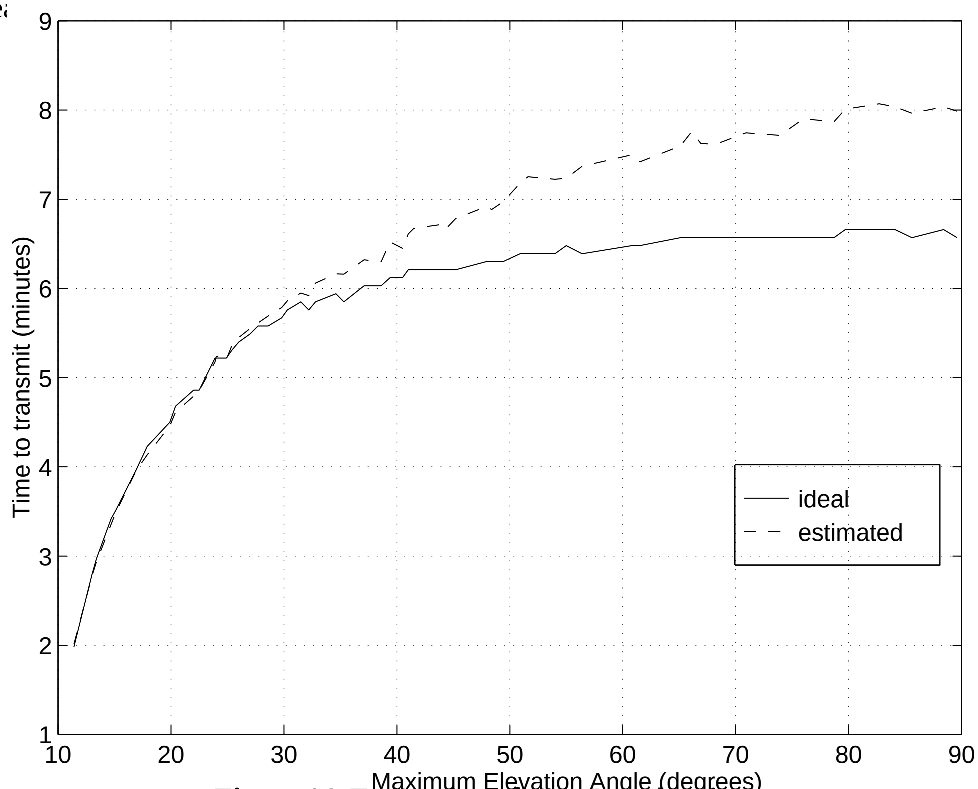

Figure 14. Estimation of zero Doppler time.

Recently, we have derived a closed form expressions approximating the Doppler-time curve as a function of maximum elevation angle [10]. In the same paper, we have also derived analytic expressions for estimating the maximum elevation angle and zero-Doppler instant based on two Doppler and Doppler-rate measurements. This estimation technique is more accurate than the one presented in the paper here.

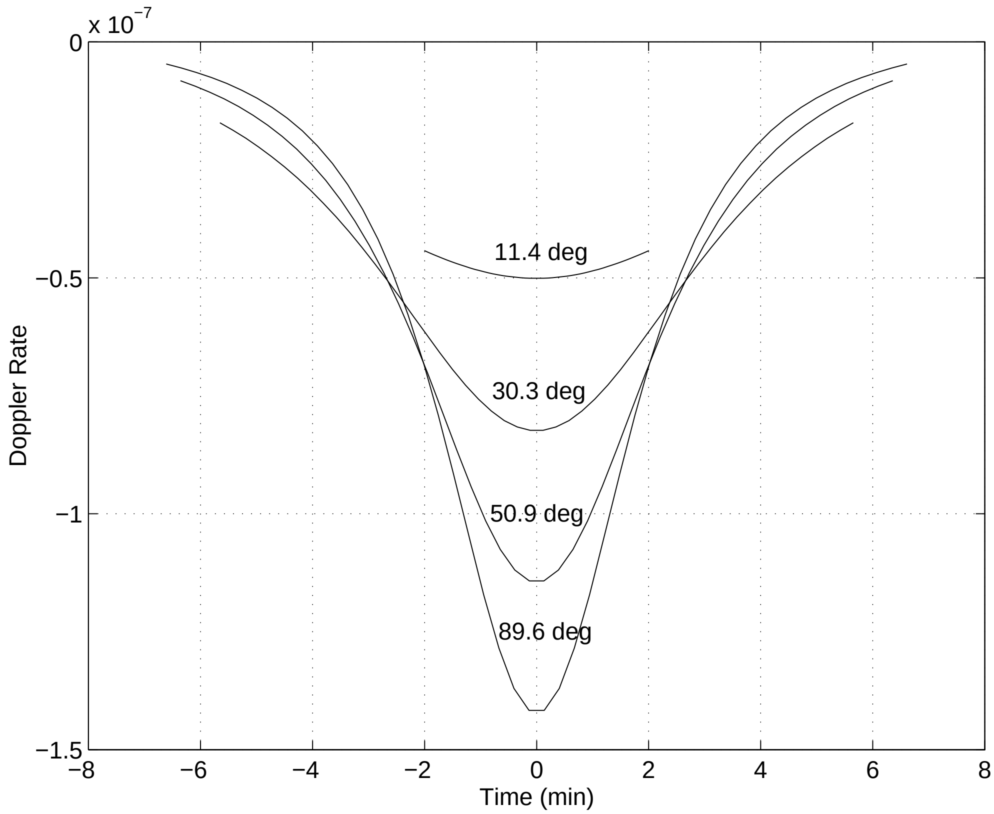

Figure 15. Rate of change of Doppler vs. time for maximum elevation angles 11.4^0, 30.3^0, 50.9^0 and 89.6^0.

6 Conclusions

The Doppler-time S-curve observed by terminals on the outbound downlink channel (from satellite to terminal) due to the relative motion between the satellite and the terminal has been used in a novel way to provide flow control in a LEO satellite messaging communication system. The control scheme, DBMA, uses two parameters of the Doppler S-curve, namely, maximum elevation angle and zero-Doppler time to specify a region of eligibility (ROE) for transmission from terminals. Only terminals inside the ROE are allowed to transmit. The size of the ROE can be modified by controlling two parameters to provide a highly effective flow control method for traffic on the inbound channel. Through computer simulations, we illustrated the effectiveness of DBMA. We also showed that quadratic curve fitting of Doppler frequency measurements is fairly accurate for a wide range of maximum elevation angles. DBMA promises to be a very powerful and effective method for flow control for LEO satellite systems.

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