A Real-time Dynamic Space Segment Emulator

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ABSTRACT

In this paper, an advanced Real-time Dynamic Space Segment Emulator (RDSSE), capable of emulating many satellite system characteristics is presented. The paper address the requirements for any such emulator and report on the result of the work carried out on development of the most comprehensive space segment emulation system.

I. INTRODUCTION

Design and development of any satellite system requires regressive testing and optimisation of the satellite payload, User Terminal (UT), and the Land Earth Station (LES). In practice, most of the UT and the LES development and testing would have to take place in parallel with the development of the satellites under laboratory conditions. This implies that the impact of constellation dynamics, propagation effects, user mobility and many other characteristics of the eventual system on the performance of various system components cannot be fully investigated and measured until the system is in place. Furthermore, as various terminal manufactures around the world would be designing UT and LES units or components, it is of vital importance to be able to type-approve, test and optimise performance under realistic conditions through the use of Real-time Dynamic Space Segment Emulator (RDSSE) platforms.

Design of any such unit is constrained by several requirements, namely the real-time emulation of the propagation channel, dynamics of the constellation (changing delay and Doppler, etc.) and various other system characteristics demanding a fast yet accurate implementation at a designated IF/RF. The presented RDSSE mainly consists of a hardware and a software module. The research and development work has been partly carried out within SINUS (Satellite Integration into UMTS) and SUMO (Satellite-UMTS Multimedia Demonstrations), two European ACTS project dedicated to development and demonstration of a W-CDMA based satellite UMTS system. What makes the developed RDSSE unique is the advanced controller software. Consequently, the major part of the presented work here is dedicated to describing various software modules.

The paper is organised as follows, the emulator requirements are identified in section-2. This leads to selection of the appropriate hardware configuration in section-3. Section-4 provides a comprehensive treatment of the advanced control software. Finally, the specification, performance, limitations and possible improvements to RDSSE are described.

II. REQUIREMENTS

The real-time emulation of propagation characteristics in the land-mobile satellite systems exploiting dynamic satellite constellations initiated this development. However, the developed emulator has come a long way since it was initially specified and is now much more capable than any commercially available system. As shown in *Figure 1*, the developed system is capable of real-time emulation of the propagation characteristics, payload non-linearities, antenna pattern, user mobility and many other system characteristics.

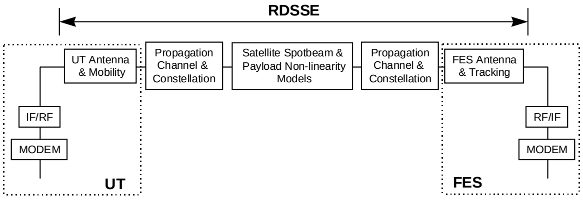


Figure 1: functional model of a single emulator link

Dynamic satellite constellations are capable of providing multiple satellite visibility (satellite diversity). It is therefore important to emulate several links simultaneously. Different configurations of the emulator links can provide emulation of a wide range of scenarios. Amongst these configurations, the spotbeam and satellite handover and combined/switched diversity are the main configurations of interest.

Operational environment	*Open/highway, lightly wooded, heavily wooded, suburban and urban*
Frequency band	*L, S, X, Ka Ku and EHF*
Constellation	*LEO66, LEO48, MEO10, GEO or other user defined constellations*
Initial orbital phase	*Allowing user the choice of the constellation starting phase to enable the trials at worst case and best case elevation angles, etc.*
Satellite spotbeam configuration	*A complete set of satellite spotbeam configurations as well as antenna patterns in addition to possibility of having user defined configurations*
FES antenna and tracking error model	*A configurable feeder link tracking error model*
UT and FES co-ordinates	*Longitude and latitude*
UT speed	*Stationary to 300km/h*
UT route, direction	*Direction of the mobile movement and provisions for possible operational environment changes during a run.*
Satellite payload characteristics	*Payload characteristics such as the amplifier non-linearities*
Traffic distribution	*User defined traffic distributions enabling realistic real-time interference emulation*
Forward-link Doppler and delay pre-compensation	*Doppler and residual delay between two diversity links can be pre-compensated by the FES in the forward-link*

Table-1:Configuribility Requirements

Through the use of a graphic user interface (GUI), the user can define a set of parameters some of which are listed above in Table-1.

III. HARDWARE EMULATION PLATFORM

There are a few hardware platforms capable of such real-time emulation, but their capability is largely constrained by the absence of a comprehensive software which generates the emulation sample points for any given desired real life scenario. The available hardware platforms can be categorised into two main families,

- *Real-time DSP-based emulation:* generates fast phase, amplitude, frequency changes internally based on a pre-defined set of statistical distributions.
- *Real-time play-back emulation:* create the desired impairments by pre-loading the fading sample points and FIR filtering of the input signal.

The former is the preferred platform as pre-loading the sample points would require large amounts of on-board memory which imposes limited run-time. On that note the NoiseCom emulation platform was selected, since it has combined characteristic of both families.

The selected hardware consists of one NoiseCom Satellite Link Emulator (SLE-250) capable of emulating 2 full-duplex paths and two multipath fading emulators (MP-2700) each capable of emulating one full-duplex link as shown in *Figure 2*. The SLE-250 is capable of generating varying Doppler shift, propagation delay, path loss, and slow fading. Each half-duplex MP-2700 link emulates direct path component and two echoes with Ricean and Rayleigh fading statistic respectively. The complete RDSSE unit is hence capable of emulating two full duplex channels which represent the radio link between two satellites/spotbeams and the UT.

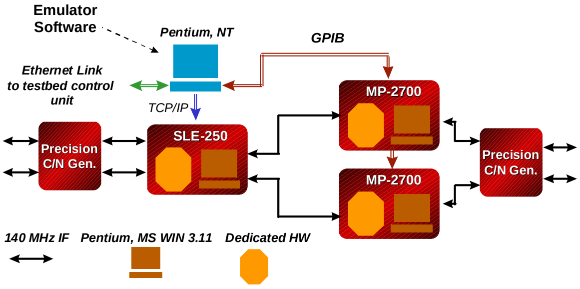


Figure 2: RDSSE Hardware Configuration

In order to be able to realistically emulate the relative characteristics of the two link within a given constellation, all the hardware units have been externally synchronised by the emulator controller unit. The two precision C/N generator units in *Figure 2*, enable introduction of dynamic interference and thermal noise during a run according to the configured scenario. The considered configuration is currently capable of coping with a maximum 10MHz input bandwidth.

IV. DYNAMIC EMULATION SOFTWARE

a. Software Architecture

The RDSSE software consists of three main sections, the dynamic satellite constellation generator, the wideband channel model for all the environments and the elevation/azimuth angles followed by the interference generator module. Through the use of a graphic user interface (GUI), the user can define the desired set of parameters.

The interaction between different software modules is depicted in *Figure 3*.

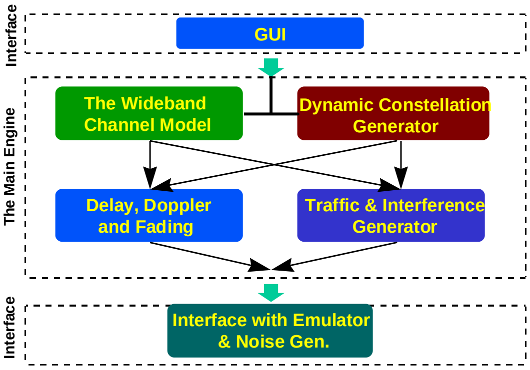


Figure 3: Software configuration

The dynamic constellation generator provides a series of relevant information such as the elevation angle of the two highest satellites/spotbeams, the azimuth separation angles, Doppler and delay (compensated or uncompensated), etc. to other software modules of the RDSSE controller. The RDSSE controller would then produce the necessary files for a given set of parameters. This file also includes other relevant information required by various hardware platform units to reflect the dynamic nature of constellation dependant changes in real-time.

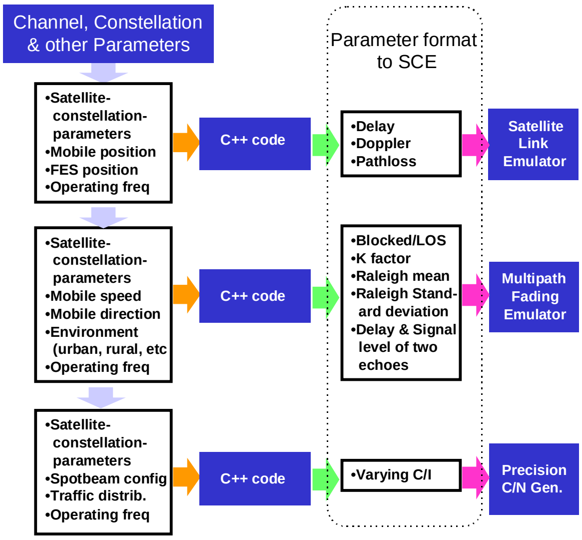


Figure 4: Sample point generation process

Figure 4, shows the logical input/output to and from the controller software unit more clearly. The format of the environment dependent parameters is that of a dynamic link library (DLL). By selecting the appropriate DLLs (via the GUI), different operational environments can be emulated. This ensures complete flexibility for user defined environmental DLLs to be simply plugged into the software if deemed necessary.

b. Constellation Generator

Within elliptical and circular orbits, only circular orbits are considered here. At present, there are two common methods, street of coverage method and spherical triangle method, for arranging satellites in a circular orbit constellation that result in efficient satellite coverage. Each method divides the satellites up into separate orbital planes containing equal numbers of satellites. *Figure 5*, shows the input parameters required to described a circular constellation. Additional parameters are required to define elliptical orbits, however these are not fully discussed in this paper.

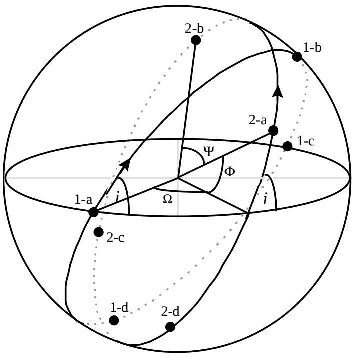


Figure 5: Satellite constellation structure

The angle Ψ represents the earth centred angle between satellites in the same plane. For a constellation plane containing N satellites Ψ is given by:

$$\Psi = {}^{360}\!/_{N}$$

The angle Ω represents the difference in the Right Angle of the Ascending Node (RAAN) between two adjacent planes. For a constellation containing M orbital planes Ω can either be:

$$\Omega = {}^{360}\!/_{M} \text{ for inclined or } \Omega = {}^{180}\!/_{M} \text{ for polar orbit}$$

The angle Φ represents the phase angle difference between satellites adjacent planes. Consider plane 1 shifted around so that it lies on plane 2, the angle Φ is the earth centred angle between satellites 1-a and 2-a. Finally the inclination angle *i* determines how high in latitude the orbital planes travel i.e. the maximum latitude reached by satellite in an orbital plane corresponds directly to the inclination angle of the plane. With inclined orbits, the inclination angle can be optimised to provide better coverage over regions where traffic is expected to be very high. When the inclination angle of an orbit is less than 90° it is called a *pro-grade* orbit. Orbits with inclination angles greater than 90° are *retro-grade* orbits. When a satellite is inclined at 90° it is said to be in a *polar* orbit. Each orbital plane is defined separately in terms of the following parameters

- Altitude - this parameter specifies the height of the orbital plane above the earth's surface.
- Inclination angle - This inclination angle of the orbital plane as described above.
- Number of satellites - The number of satellites in the orbital plane. The satellites are distributed evenly within the 360° of the plane.
- Number of planes
- RAAN - Right Ascension of the Ascending Node. This angle is equivalent to Ω above. It is measured from the Vernal Equinox to the ascending node. The ascending node is the point where the satellite passes through the equatorial plane moving from south to north. Right ascension is measured as a right-handed notation about the pole.
- Mean Anomaly - represents the fraction of an orbit period which has elapsed since perigee. For a circular orbit the mean anomaly equals the true anomaly.
- Argument of Perigee (elliptical orbits)- The angle from the ascending node to the eccentricity vector measured in the direction of the satellite motion. The eccentricity vector points from the centre of the Earth to perigee with a magnitude equal to the eccentricity of the orbit.
- Eccentricity (elliptical orbits)- Defines the shape of the ellipse.

c. Spotbeam Antenna Models

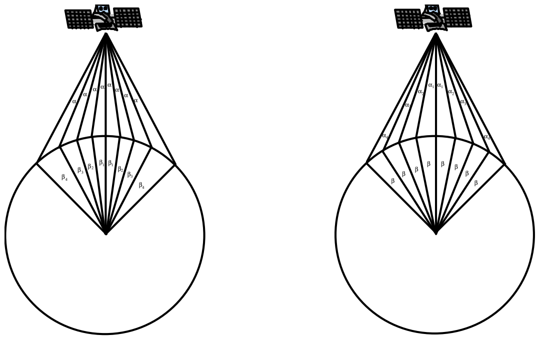

(a) (b)

Figure 6: Antenna spotbeam arrangement

Two mainly identified spotbeam models are shown in *Figure 6* and the projection of the spotbeams on the earth is shown in *Figure 7*.

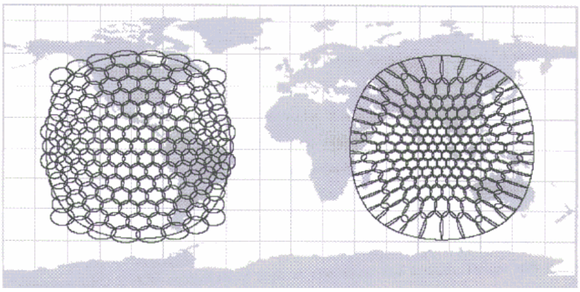


Figure 7: Projection of spotbeams on the earth

But, for the second case, with equal beam width, the distortion in the outer ring is high. This can be compensated as shown in the first case by varying the beam width of the spotbeam. These phenomena is incorporated with the software. Detail about the beam width calculation can be found [6].

d. The Propagation Channel Model

When a mobile user moves through the communication environment, the signal received by the user is blocked time to time due to LOS obstructions around the user. Furthermore, in non-geostationary satellite constellations the relative position of the satellite also changes causing similar shadowing impairments. This leads to a large drop in the signal strength commonly referred to as shadowing. Signal variation during shadowing is modelled using Loo's model [2] In the proceeding sections of this paper, the shadowed and the non-shadowed cases are referred to as bad and good state, respectively. The bad and good duration are measured in terms of distance for a required environment and the measured values are incorporated within a two state Markov model for a single user-satellite link. Within any given states, there are signal strength variation due to the multipath effect. *Figure 8*, shows the narrowband representation of a typical received signal, highlighting various fading elements and parameters considered in the RDSSE software.

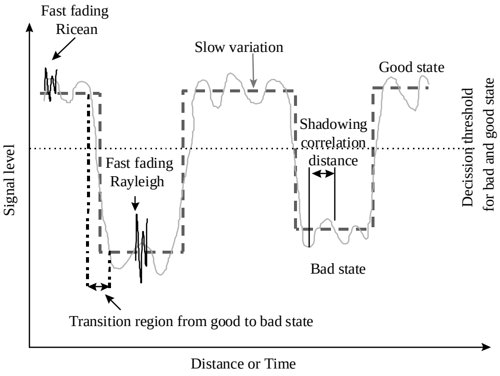


Figure 8: Received signal (narrowband representation)

The narrowband propagation parameters such as the shadowing statistics for various operational environments have been extracted from large experimental databases of University of Surrey[5] and combined with that of the DLR [4] results in order to provide a harmonised European model. *Figure 9*, shows how the space and ground segment propagation effects can be treated separately.

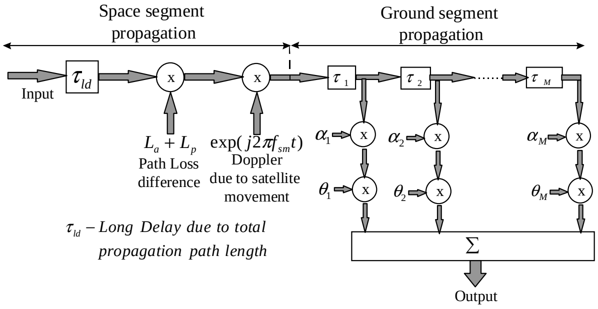


Figure 9: Complete Propagation Model

Note that as far as the path loss implementation is concerned, only the variation between the centre of the footprint and the terminal position are emulated due to the limited dynamic range of the attenuators of the hardware platform. However, external attenuators can be employed to increase the dynamic range if necessary. The ground segment propagation part represents the multipath effect and fading due to shadowing. The above wideband model can be used for both shadowed and non-shadowed cases by just changing the parameters θ & α of each tapes. The wideband satellite channel model of the ground segment has been developed based on actual recordings. Analysis of the results generally show delay spreads of 100ns or less. At higher elevation angles and open environments there are not many multipath components. As far as multipath is concerned, low elevation angles of the urban environment have been found as the most hostile environments. *Figure 10*, shows the power-delay profile of one such urban environment at 45° at L-band. It can be observed that even in the urban environment, all the resolvable echoes arrive very close to the LOS signal. *Figure 11*, shows the time aligned version of the above figure used in development of tap-delay-line models.

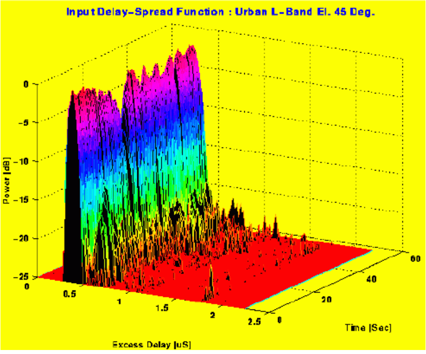


Figure 10: Power Delay Profile, L-band, 45°

As shown in *Figure 11*, no more than 2 major reflections are encountered in this particular case. Furthermore, the average power in the reflected components are generally about 15-30 dB below the average power of the LOS component.

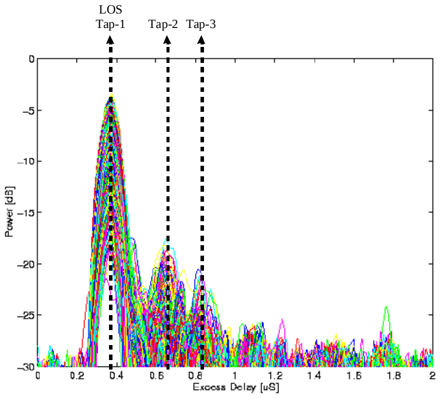


Figure 11:Time-aligned Power Delay Profile, L-band, 45°

But nevertheless, at lower elevation angles the LOS is significantly attenuated resulting in much higher reflected powers (relative to the LOS). A comprehensive set of tap-delay-line models for all the elevation angles and environments has been developed, enabling wide range of channel emulator operation. The LOS has been found to be generally have a Rician fading and the reflected components a Rayleigh distribution. It is important to point out that the relative delay of each tap varies in time as the distance between the mobile user and the reflector changes. Assuming conventional fixed tap-delay models one cannot hence test many system algorithms such as the performance of the RAKE receiver tracking algorithm.

Therefore in tapped-delay-line model of *Figure 9*, the tap delays and their relative power does not stay constant for a duration of a run. Extensive analysis of the data has resulted in a definition of a new tap-delay-line models enabling realistic wideband channel representation [1].

e. Azimuth Correlation

Satellite diversity can be employed as an effective tool for combating shadowing and hence achieving higher service availability figures. However, in realistic diversity scenarios, some correlation between the shadowing of the diversity satellite channel links exists depending on the azimuth separation angle, operational environments, constellation and the elevation angle. In order to be able to represent this accurately, fish-eye pictures of various operational environments have been taken. *Figure 12*, shows one such picture taken in central London, representing a typical European urban environment.

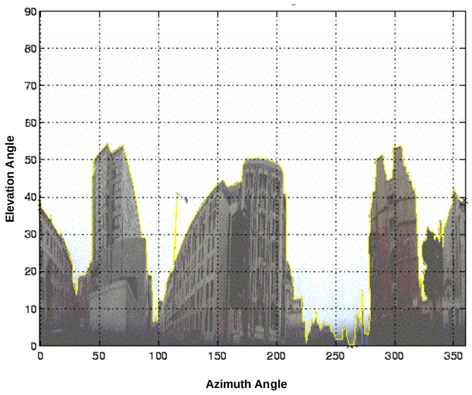


Figure 12: Fish-eye picture of urban env., London

Through the use of edge detection algorithm, shadowing profiles have been extracted as shown in *Figure 13*.

The autocorrelation of the above shadowing profile provides the all important azimuth correlation coefficient used to determine the shadowing likeliness of the diversity channels. A complete set of azimuth correlation coefficients for all the operational environmental categories have been developed and utilised within the SCE software to represent realistic diversity scenarios. In order to incorporate, the azimuth correlation, the four state model proposed by Lutz [3] was utilised. Full detail of the Morkov model can be found in this reference. *Figure 14* shows the correlation coefficient of two satellites at 45° elevation angle with variation in azimuth angle.

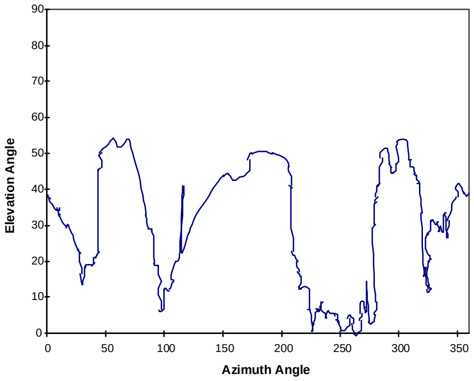


Figure 13: Shadow profile of urban env., London

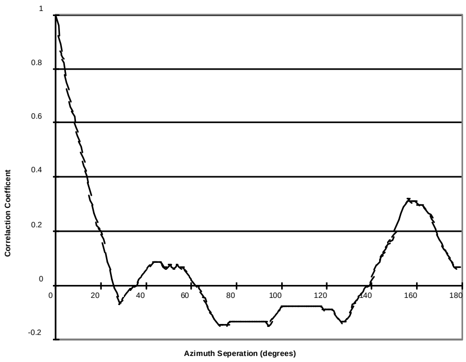


Figure 14: Variation of correlation coefficient

f. The Interference Module

Interference within any single system is caused by:

- users distribution in the spot beam of interest
- user distribution in the adjacent spot beams of satellite
- user distribution in the adjacent satellite spot beams

as shown in *Figure 15.*

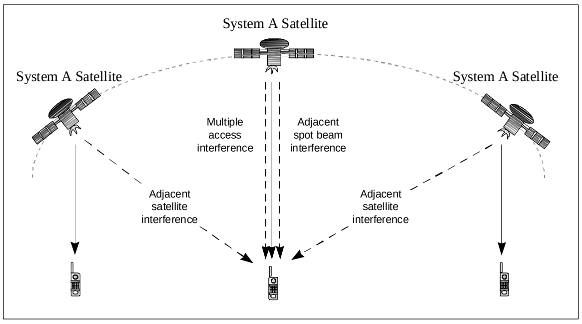


Figure 15: Sources of multiple access interference

It is realisable from the above, that interference not only comes from spot beams of the same satellite, but also from other satellites. Due to the dynamic nature of the considered constellations, the level of this interference varies as formation of spotbeam patterns with different overlapping move over the surface of earth. It is therefore of vital importance to be able to test and evaluate the performance of system under such conditions. The considered interference module generates the real-time varying interference based on a comprehensive set of input parameters. *Figure 16*, shows an example of the varying C/I for a LEO-based system.

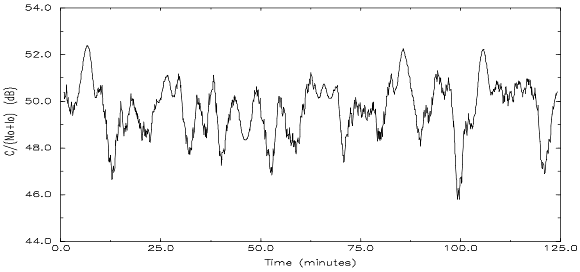
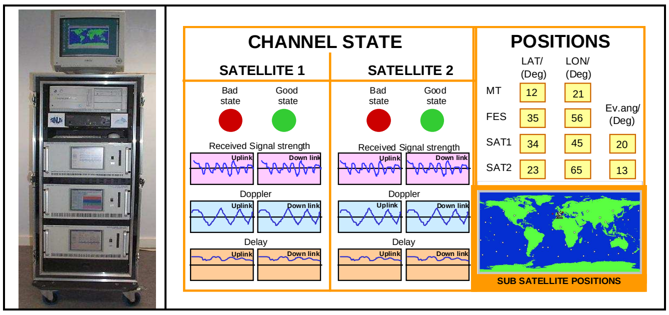


Figure 16: Real-time C/I variations in a typical LEO

V. PERFORMANCE SUMMARY

We have developed an advanced Real-time Dynamic Space Segment Emulator (RDSSE), capable of emulating any mobile satellite system in real time. The RDSSE arrangement is shown in *Figure 17*(a). The controller displays the channel state during run time for monitoring purpose as shown in *Figure 17*(b). The software has a most comprehensive wide band land mobile satellite channel which includes a varying tapped-delay-line model (varying delay and power of echoes with time). The model also takes in to account the azimuth correlation between two satellite channels, which can greatly improve satellite availability. The RDSSE is capable of testing the performance of a new future mobile satellite system, User Terminal (UT), and the Land Earth Station (LES) before operation, without the need to have the system in place. This will help the terminal manufactures to test and optimise performance of their UT and LES units under realistic conditions through the use of RDSSE platforms. The RDSSE can also be used to test the signaling, call set-up procedures, power control algorithms, dual satellite diversity and handover procedures (inter-spotbeam handover and inter-satellite handover). This makes RDSSE one of the most advance mobile satellite system testing tool for any constellation.

Since, it has only two duplex channels, the handover performance with diversity can be tested. In order to over come this, one more duplex channel should be added with this arrangement. Due to the limitation in minimum update interval(0.1s), very smooth transition for good state to bad state or vice versa can't be achieved.

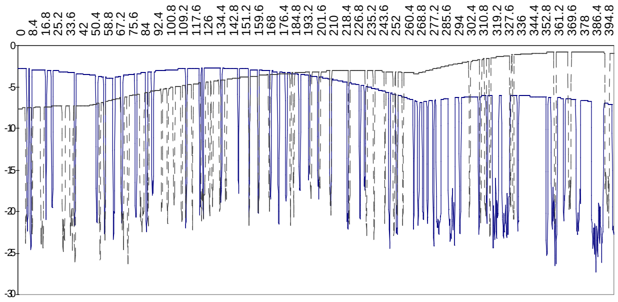


POSITIONS

	LAT/ (Deg)	LON/ (Deg)	Ev.ang/ (Deg)
MT	12	21	
FES	35	56	
SAT1	34	45	20
SAT2	23	65	13

(a) RDSSE (b) Monitoring GUI windows for RDSSE

Figure 17



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