A CDMA SPOTBEAM ARCHITECTURE FOR THE NEXT GENERATION SATELLITE SYSTEM (NGSS) FOR THE AERONAUTICAL TELECOMMUNICATIONS NETWORK (ATN)

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Project Overview

"The current air transportation system in the United States is experiencing significant delays, decreased efficiency and increased costs. This is especially true during adverse weather conditions. The Air Transport Association estimates that the current delays in the system result in an annual operating loss in excess of $3 billion per year for US airlines.

Over the next 20 years, the demand for air travel is expected to double, making these problems much more severe unless new capabilities are developed and made operational. The FAA estimates that the number of airports with major delays would double in the next 20 years. An American Airlines study estimates that flight delays would become so severe that they would not be able to maintain the integrity of their flight schedules." [1].

NASA's Aerospace Technology Enterprise has established a goal to increase the capacity of the nation's airspace to keep up with these demands. Specifically, "While maintaining safety, double the aviation system throughput, in all weather conditons, within 10 years and triple within 25 years." [1].

To respond to this technology objective, NASA created the Airspace Systems Program, which has developed a roadmap to meet this objective. One step on this roadmap is the Advanced Air Transportation Technologies (AATT) Project. AATT's objective is to improve the overall performance of the National Airspace System (NAS) as a whole. To meet this objective, AATT is developing decision support technologies and procedures to aid NAS stakeholders. The vision of the AATT Project regarding far-term operations is embodied in the Distributed Air/Ground Traffic Management (DAG-TM) concept.

DAG-TM is most succinctly defined in its Vision Statement:

"*Distributed Air/Ground Traffic Management is a National Airspace System concept in which flight deck (FD) crews, air traffic service providers (ATSP), and aeronautical operational control (AOC) facilities use distributed decision-making to enable user preferences and increase system capacity, while meeting air traffic management requirements. DAG-TM will be accomplished with a human-centered operational paradigm enabled by procedural and technological innovations. These innovations include automation aids, information sharing and Communication, Navigation, and Surveillance (CNS) / Air Traffic Management (ATM) technologies.*"[2]

This paper will present work being done to model and simulate a CDMA based Mobile Satellite System architecture for providing all or part of the future Air Traffic Management (ATM) services. Such a system, will help in relieving the dependence on ground based networks, if not eliminate it. Additionally such an architecture can be used in parallel or as a supplementary service along with ground based links to help alleviate any capacity bottlenecks, or in areas where such services are difficult to make available such as in oceanic, remote areas outside the jet highways, or in developing countries where ground services are less available.

The architecture assumes 9,000 simultaneous air-to-ground links of 1 kbps. This is a forecasted traffic load for the year 2020. A typical 27 MHz transponder bandwidth, divided into four 6.75 MHz sub bands, could accommodate 625 users per sub band, for a total of 2500 users per transponder. Hence, four transponders suffice to provide for the required peak number of aircraft. The analysis assumes 3 Mchip/sec chip rate for the CDMA accessing scheme and includes _ rate convolutional coding added onto the 1 kbps QPSK-modulated raw data rate. Including downlink rain fade margins, an overall link margin of 2.8 dB yields a 99.9% availability. (In all cases discussed the required bit-error rate is assumed to be 10^{-6}). Hub terminal antennas of 2 meters diameter were required [3].

For this system, the ground-to-air link assumed twenty 500 kbps CDMA broadcast links, which enabled a 3.0 dB margin to be maintained, including rain fade, to yield a link availability of 99.9%. The link included _ rate convolutional coding on top of the 500 kbps raw QPSK data rate. A single 27 MHz transponder can provide the ground-to-air requirements. [3].

Research Scenario

Return Link (air to ground)

An OPNET [4] model was constructed for the CDMA satellite communication (SATCOM) scenario in question. The sources of traffic were 524 aircraft observed traveling through the Dallas / Ft. Worth En Route Air Traffic Control Sector (ZFW ARTCC) over a period of one hour on 6 Sep 2000. The traffic file was obtained from the FACET program at NASA Ames [5]. At any given instant of time, a little over 200 aircraft were actually within the sector's airspace. The moving aircraft were broadcasting Automatic Dependent Surveillance (ADS) traffic, in accordance with the message frequency specified in [6]. The messages were broadcast on a Ka Band uplink frequency of 29.75 GHz with a bandwidth of 6.75 MHz. The data rate of the messages was 1 kbps, and each aircraft had its own CDMA spreading code. The broadcast power was 14.4 watts and the modulation scheme was QPSK [3].

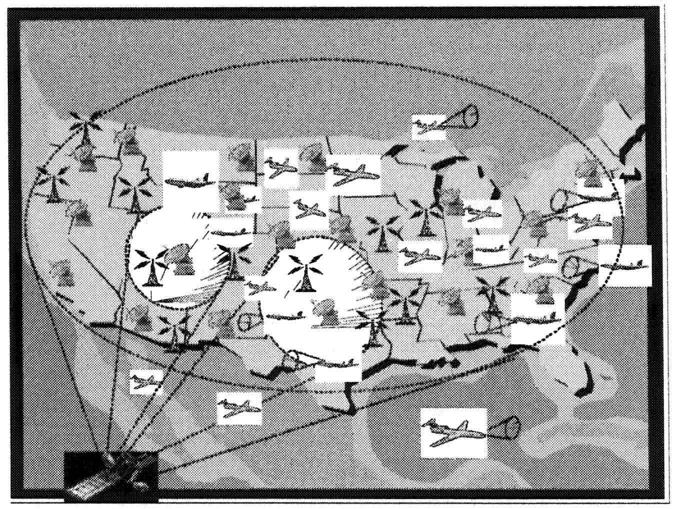

Figure 1. Satellite System Architecture

The ADS messages were transmitted via a directional antenna to a Ka Band satellite at 101 degrees West Longitude over the equator. The satellite in question was a simple bent pipe which retransmitted all received energy back to the earth at a transmit frequency of 19.95 GHz. The satellite had an on-board directional antenna pointing to 33 degrees North latitude, 97 degrees West longitude, or effectively, the center of the ZFW ARTCC. Once again, the bandwidth was 6.75 MHz and the data rate was 1 kbps. The transmit power at the satellite was 7.94 watts to be shared by all channels, and the modulation scheme was QPSK. The assumption was that all energy received at the satellite would be transmitted back to earth on a channel-by-channel basis, with each channel corresponding to the different spreading codes of each aircraft transmitting messages to the satellite.

The ADS messages were relayed by the satellite to a ground station co-located with the Dallas / Ft. Worth Air Traffic Control Center. Each CDMA channel at the ground station had a processing gain of 34.77 dB, which is shown in the link budget in Table 1.

For the ground station, the throughput, utilization, collision status, and packet loss ratio for a single CDMA receiver channel are shown in the two graphs below.

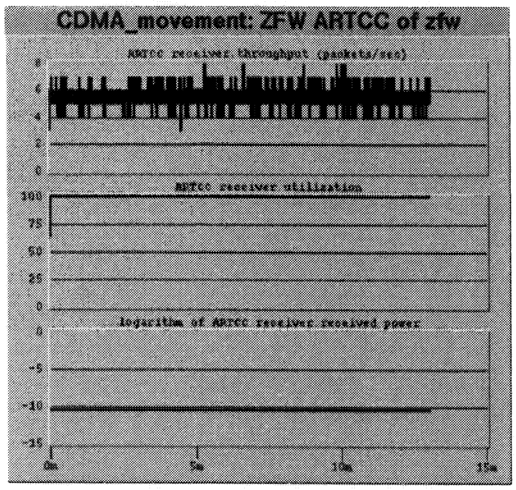

Figure 2. Ground Receiver Throughput

It can be seen that individual ground station channels receive between 5 to 6 packets per second, which is expected since that is approximately the rate of transmission of ADS-B packets as per [5] for a single aircraft, as that was chosen as our traffic source for this simulation. The receiver utilization (the percentage of time that the receiver is busy) is 100%, because of the presence of interfering ADS-B channels from other aircraft on other CDMA channels.

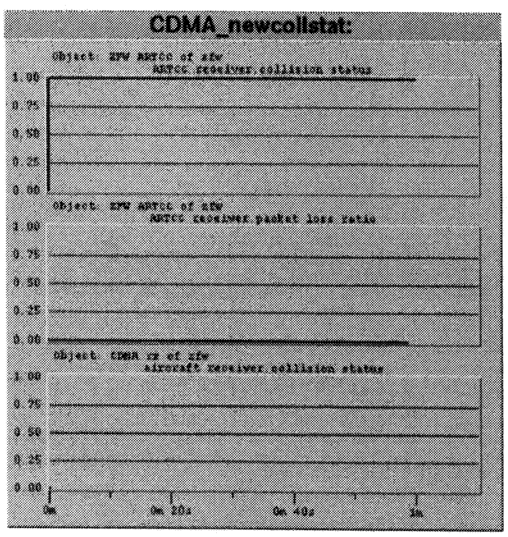

Fig. 3. Ground Receiver Collision Status

The collision status, a Boolean value, is constant at 1.0, indicating that collisions are always occurring. However because this system is a CDMA system where each receiver channel at the ground station is tuned to a particular spreading code, the packet loss ratio is zero.

We can extrapolate from the receiver throughput for a single receiver channel to determine the required data rate for the ground station transmitter, which retransmits all the collected information back to the aircraft as TIS packets. The incoming packet rate is 6 msg / sec-channel as seen in Figure 2. The length of a packet is 112 bits. (This is because we retained the Mode S packet formats from [7], just as we reused the Mode S ADS-B traffic generator.) The maximum number of channels we expect a ground station receiver to support is 625 users in a 6.75 MHz band.

*6 msg/sec-channel * 112 bits / msg * 625 channels = 420 kbps.*

If seven messages per second were chosen, the data rate needed would be 490 kbps. A data rate of 500 kbps for the link from each ground station back to the aircraft should be sufficient.

Therefore our simulation used that data rate per ground station, giving a total data rate of 10 Mbps for the CONUS. There are twenty ARTCC ground stations in the CONUS, each of which could use a separate spotbeam at the same frequency. The messages on the forward link contain TIS information generated from the incoming ADS and use the same Mode S packet format. This is seen in the ground-to-air section of this paper.

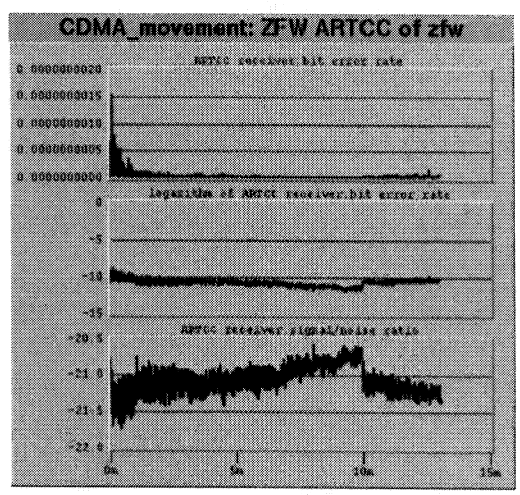

Fig. 4. Ground Station SNR & BER

Figure 4 shows the signal to noise ratio and the bit error rate at the ZFW ARTCC ground station receiving the sector's ADS traffic from the satellite. The signal-to-noise ratio at the ground station is no worse than -21.75 dB. In OPNET, this is the ratio of signal power to noise power C/(N+I) and not that of bit energy to noise density (E_b/N_o). In this version of the OPNET simulation, the background noise only consists of the contribution from the downlink, since in OPNET, the satellite is a node which receives packets and then retransmits them as packets. A bent-pipe can only be approximating by ignoring SNR and BER at the satellite and simply retransmitting all packets, including overlapping ones. Future enhancements to our simulation will include the calculation of background noise on the uplink to be stored in a data structure that accompanies each packet on the downlink.

Working backwards from the observed C/(N+I), and ignoring background noise for the moment, one can calculate the worst case number of interferers that a packet observes.

C/I = -21.75 dB; I/C = $10^{2.175}$ *= 149.6 or 150 interferers per channel.*

The vast majority of transmitted traffic is successfully received at the ground station, mainly due to the processing gain of 34.77 dB, seen in the link budget, which boosted the received signals from the initially low SNR. Adding the processing gain also converts C/(N+I) to E_b/N_o used to look up the BER in a QPSK modulation table in OPNET.

As it were, the Mode S packet format used in our simulation has a 24-bit parity field which can correct any 12 bit errors in the 112-bit packet, or up to 10.7% of errors. Convolutional coding further improves this performance. The Mode S Extended Squitter packet format is shown in the figure below.

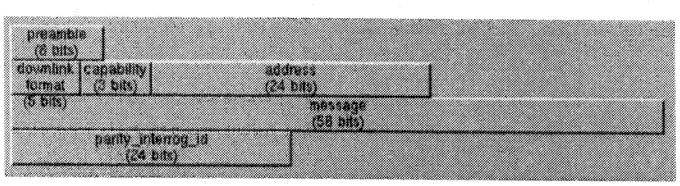

Figure 5. Extended Squitter Packet Format

Forward Link (Ground to air)

At the ground station the received ADS traffic was merged into a single channel using a FIFO queue and transmitted as a stream of Traffic Information Service (TIS) messages. The TIS stream was relayed to the satellite at a frequency of 29.78 GHz, with a bandwidth of 27 MHz, again using QPSK modulation with _ rate convolutional coding. The ground station had a transmit power of 50 watts, and transmitted on a single CDMA output channel to the satellite via a directional antenna. In an actual implementation, we assume (although not required) there would be twenty such ground stations co-located with the twenty regional air traffic control centers in the United States, each uplinking to the satellite using QPSK at the same power, bandwidth and frequency, but each with a distinct spreading code. In this simulation, only one such ARTCC was modeled. As can be seen in Figure 6, there was no queue buildup at the ground station, since the data rate of 500 kbps was sufficient to transmit all arriving packets.

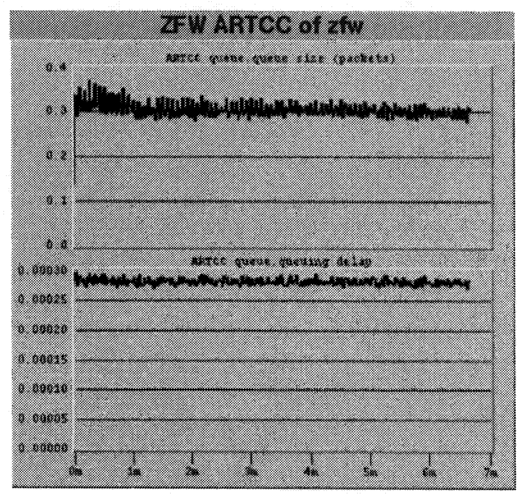

Fig. 6. Ground Transmitter Queue

Just as with the case of the ADS messages from the aircraft to the ground, the satellite at 101 degrees West Longitude relayed the 500 kbps traffic in a bent-pipe fashion at an output power of 7.94 watts, but this time at a frequency of 19.98 GHz and with a bandwidth of 27 MHz. The TIS traffic was retransmitted to receiving aircraft with the same spreading code as the incoming message to the satellite on the link from the ground station.

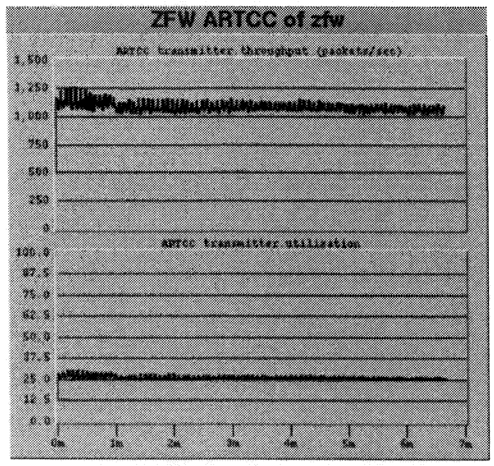

Figure 7. Ground Tx. Throughput

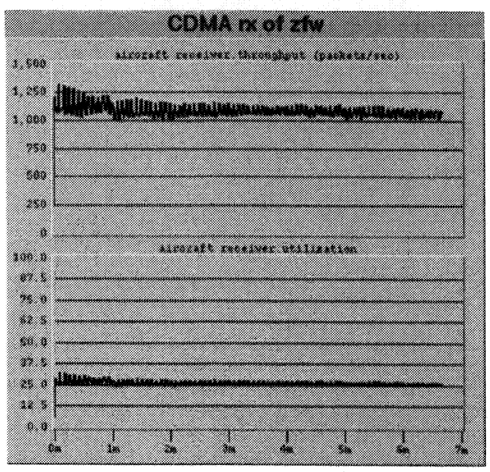

Figure 8. Aircraft Rx Throughput

Figures 7 and 8 show the throughput of the TIS traffic at the ground station transmitter and the aircraft receiver. The numbers are virtually identical. This demonstrates that the bent pipe model of the satellite in the simulation is working correctly. It also shows that virtually all packets are received at the aircraft without loss. Only one ground station is transmitting here. This limitation will be addressed in a subsequent section.

Another fact we can glean from the ground station throughput is the number of aircraft transmitting at any one time in the scenario. We saw at the ground receiver that for a single channel the packet rate was from 5.5 to 6 msg/sec. The throughput shows that 1100 to 1200 TIS packets are transmitted per second. This suggests that during the course of the simulation roughly 200 aircraft are regularly transmitting. This is borne out by information in the data file used to create the air traffic scenario. At any given timestamp in the data file, there were roughly 200 aircraft with trajectory points. In other words, roughly 200 aircraft were recorded as moving within the ZFW enroute sector during that one minute interval between trajectory points.

Since there is only one channel of TIS traffic in this simulation, we observe a Carrier-to-Noise Ratio of 7.6 dB (not shown here), which results in a BER of virtually zero based on QPSK modulation. We can calculate an expected C/I with our assumption of 20 ground stations co-located with each of the enroute ARTCCs in the CONUS.

$$10*log_{10}20 = 13\ dB = I/C.$$

$$C/I = -13\ dB.$$

We then take into account that we are transmitting a 500 kbps signal spread over a 27 MHz bandwidth. The symbol rate will also be 500k since the QPSK signal is coded with a _-rate convolutional coder. So we see an effective processing gain at the receiver of 17.3 dB. This gives us a positive Eb/No of 4.3 dB, which in QPSK should result in a bit error rate of roughly 0.01, which can be corrected by taking advantage of parity bits and coding.

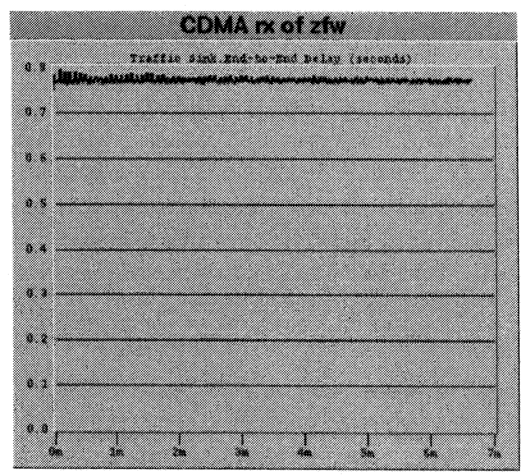

Figure 9. End to End Delay

Finally we take note of the end-to-end delay in the system, or the time between packet creation and its reception at a receiver aircraft after air-to-satellite-to-ground and ground-to-satellite-to-air transmissions. Figure 9 shows us that this is approximately 0.8 seconds total. The time it takes for electromagnetic energy to travel two round trips from aircraft at an average altitude of 10 km via a ground station at sea level is as follows:

$$(2*(35,786\ km - 10\ km) + 2*35,786\ km) / 300,000\ km/s = 0.477\ seconds$$

This demonstrates that our link also has approximately 325 ms of processing time during the two round trips.

With the exception of the use of the Ka Band, the results described above can be compared with specifications for Next Generation Satellite Systems (NGSS) in [8].

Recommendations for Future Work

One area of recommended research would be to simulate several sectors (using several spotbeams) simultaneously using a maximum of 625 aircraft per sector [3]. Nonetheless, our experience shows that the simulation environment we used did not have sufficient computing power to process this level of traffic.

Other areas of research can investigate the use of more complex channel models than those used in the current simulation. For example, a fading model that takes into account multipath at the aircraft as well as shadowing due to turning maneuvers can provide further insight and possible enhancements to the receiver design. Another example would be to study variations in CDMA spreading schemes, error correcting codes, and modulation schemes.

Although other architectures are being looked at for NGSS, the architecture simulated in this study is a recommended one for uplink/downlink capability using CDMA and a geostationary satellite design both of which have many economical and technical advantages. A simpler receive only broadcast architecture was also studied as a possible interim alternative [9]

References

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[3] Kerczewski, Spence, et al., Emerging Aeronautical Communications Architecture Concept for Future Air Traffic Management Requirements, 8th Ka Band Utilization Conference, 2002.

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[8] RTCA, 2001, *Minimum Aviation System Performance Standards for Aeronautical Mobile Satellite Service As Used in Aeronautical Data Links*, DO-270, Washington, DC.

[9] Shamma, M., Raghavan, R., *A TDMA Broadcast Satellite / Ground Architecture for the Aeronautical Telecommunications Network*, I-CNS 2003 conference, Annapolis, MD.

Table 1. Air To Ground CDMA Accessing Link Budget Analyses [3]

Uplink Frequency (GHz)	29.750	
Downlink Frequency (GHz)	19.95	
GSO Satellite Transponder Parameters		
Uplink xponder saturation flux density (dBW/m^2)	-80.00	This is PFD at the satellite which results in max power from the sat xponder
Xponder saturation EIRP (dBW)	54.00	This is max EIRP available from sat xponder at EOC
Uplink receive G/T (dB/K)	13.90	G/T at EOC
Uplink receive noise temp (K)	575.44	27.60 dB-K
Uplink receive gain (dBi)	41.50	
Satellite Altitude (km)	35786.00	
ATC Hub Station Parameters		
Antenna diameter (m)	2.40	
Xmit gain (dBi)	55.26	
Xmit power (dBW)	17.00	50.12 watts
Xmit EIRP (dBW)	72.26	
Recv gain (dBi)	51.79	
System Noise Temp (dB-K)	26.67	464.52 K
Recv G/T (dB/K)	25.12	
Height above sea level (km)	0.00	0.00 ft
Elevation angle to satellite (deg)	40.00	
Latitude of terminal (+N,-S) (deg)	41.00	
If including rain specify:		
ITU-R Rain Zone	K	A,B,C,D,E,F,G,H,J,K,L,M,N,P,Q
Availability (%)	99.900000	(refer to ITU-R rain zone maps)
D/L rain attenuation (dB) (sat-to-hub)	6.844	Rain loss for specified RZ and Avail
U/L rain attenuation (dB) (hub-to-sat)	14.566	
Aircraft Terminal Parameters		
Number of array elements along x and y	12.00	144.00 elements total
Element spacing (fraction of wavelength)	0.60	0.60 cm
Element gain (dBi)	5.00	
Element power (W)	0.10	100.00 mW
Element power efficiency	0.30	30.00 %
Max Array gain (dBi)	26.58	
Total RF power (dBW)	11.58	
Prime power (dBW)	16.81	48.00 W
Array dimension along x and y (cm)	6.65	cm on each side
Xmit EIRP (dBW)	38.17	
Recv gain (dBi)	37.00	
System Noise Temp (dB-K)	25.00	316.23 K
Recv G/T (dB/K)	12.00	
Elevation angle to satellite (deg)	40.00	
Height above sea level (km)	11.00	36089.24 ft
Signal Modulation/Coding Parameters		
Source data rate (Rb) (bps)	1000.00	
Code rate (e.g. 1 for no coding)	0.50	
data rate out of encoder (bps)	2000.00	
Order of PSK modulation (M)	4.00	
coded bits per symbol	2.00	
Channel symbol rate Rs (sps)	1000.00	
Data Bandwidth (null-to-null = 2Rs) Hz	2000.00	
Spreading code chip rate (Rc) cps	3000000.00	
Spread bandwidth (null-to-null = 2Rc) (Hz)	6000000.00	
Spread Spectrum Processing Gain (Rc/Rs) (dB)	34.77	
Required Eb/No (dB)	4.50	(10-6 @ rate 1/2,K=7 coded QPSK)
EIRP density (peak) (dBW/Hz)	-26.60	
EIRP density (avg over spread BW) (dBW/Hz)	-29.60	
Bandwidth-limited Capacity of Xponder		
Xponder BW (Hz)	27000000.00	
User Xmit (spread) BW (Hz)	6000000.00	
Max # of Simultaneous CDMA sub-bands (M)	4.00	sub-bands per xponder
# of Simultaneous CDMA users per sub-band(N)	625.00	users per sub-band
Total # of simultaneous users per xponder	2500.00	users per xponder
Total Xponder Throughput R (bps)	2500000.00	MxNxRb

CDMA Aircraft-to-Ground Link Budget

This section computes the Aircraft-to-Ground link performance assuming CDMA and a nonregenerative (bent-pipe) transponder onboard the GSO satellite.

Parameter	Values for Single CDMA User		Values for each of M = 4 CDMA Sub-bands		Values for Total Xponder	
UPLINK						
Number of Simultaneous Users	625.00	# of users per sub-band	4.00	# of sub-bands in xpond	2500.00	Total users per xponder
EIRP (dBW)		38.17		44.19		72.15
Xmit power (dBW)	11.58	14.40 watts	17.60	57.60 watts	45.56	36000.00 watts
EIRP Density (dBW/Hz)	-29.61	over signal spread BW	-23.59	over signal spread BW	-2.17	over xponder BW
User Elevation Angle(deg)	40.00					
Coverage Angle (deg)	13.31					
Central Angle (deg)	43.35					
Slant Range to Sat (km)	37780.30					
Free-Space Path Loss (dB)		-213.46		-213.46		-213.46
Atmospheric Loss (dB)		-0.32 (from UL atmospheric loss sheet)		-0.32		-0.32
Polarization Loss (dB)		-1.00		-1.00		-1.00
Saturation Flux Density (dBW/m^2)	-80.00		-80.00		-80.00	
Recv Power Flux Density (dBW/m^2)	-125.69	from single CDMA user	-119.67	from all user in sub-band	-91.71	from all users in xponder
Input back-off from saturation (dB)					11.71 OK	Transponder IBO (dB)
Recv Antenna Gain (dBi)		41.50		41.50		41.50
Recv Signal Power (dBW)		-135.11 from single CDMA user		-129.09 from all users in sub-band		-101.13 from all users in xponder
Uplink Noise Power (dBW)		-133.22 in spread BW		-133.22 in spread BW		-127.20 across all sub-bands
Uplink Noise Power Density (dBW/Hz)	-201.00		-201.00		-201.00	
Receive G/T (dB/K)	13.90		13.90		13.90	
Received U/L C/N (dB)		-1.89		4.13		26.06
Received U/L C/No (dB-Hz)		65.89		71.91		99.87
DOWNLINK						
Xponder Saturated EIRP (dBW)						54.00
Xponder Output Backoff (dB)						4.40 Transponder OBO
Total Available EIRP (dBW)						49.60 91097.84 eirp watts
Total Uplink Power (Noise+Signal) (dBW)					-101.12	
EIRP allocated to uplink noise (dBW)					23.52	224.91 eirp watts
EIRP allocated to users (dBW)		15.60 36.35 eirp watts		43.56 22718.23 eirp watts		49.58 90872.93 eirp watts
% Xponder EIRP allocated to U/L noise						0.25 %
% Xponder EIRP allocated to users						99.75 %
Hub Elevation Angle(deg)	40.00					
Coverage Angle (deg)	13.31					
Central Angle (deg)	43.35					
Slant Range to Sat (km)	37780.30					
Free-Space Path Loss (dB)		-209.99				
Atmospheric Loss (dB)		-0.53 (from DL atmospheric loss sheet)				
Rain Loss (if included)		-6.84 99.90 % availability				
Polarization Loss (dB)		-1.00				
Hub Recv Gain (dBi)	51.79					
Hub Recv Power (dBW)	-150.97	from single CDMA user				
Hub Noise Temp	464.52 K					
Hub Noise Power (dBW)	-134.15	in spread BW				
D/L Noise Power Density (dBW/Hz)	-201.93					
Hub Recv G/T (dB/K)		25.12				
Recv Downlink C/N (dB)		-16.82 in spread BW				
Recv Downlink C/No (dB-Hz)		50.96				

Note: Using 140 active users (which is what a typical Sector Traffic would have) vs. the maximum design allowable users of 625 gives exact match results to the simulations. For example, the C/((N+I)) in section to follow would become approximately -22 db (as opposed to -28.28) shown below, with link margin increasing to 8.89 db from the 2.83 shown below, hence matching and verifying the independent Opnet simulation results. See Text

NET LINK PERFORMANCE

Net C/No (dB-Hz)	50.82	includes U/L and D/L thermal noise
Recv Signal Power C (dBW)	-150.97	receive signal power in the spread BW
Signal Values BEFORE Spread Spectrum Correlator		
Peak signal PSD (dBW/Hz)	-215.74	note this is prior to despreading by the correlator
No (dBW/Hz)	-201.79	thermal noise power density
N (dBW) (in spread BW)	-134.01	thermal noise power in spread BW
I (dBW) (in spread BW)	-123.02	CDMA interference power from N-1 other users in spread BW
Io before correlator (dBW/Hz)	-187.79	Peak CDMA interference power density at input to correlator
C/(N+I) at correlator input	-28.28	Note this is usually negative for spread spectrum at the correlator input
Signal Values AFTER Spread Spectrum Correlator		
Io after correlator (dBW/Hz)	-189.55	Note this only slightly lower than at the correlator input since the signals are spread to begin with
I at correlator output (dBW)	-156.54	Note this is interference power at output of correlator IF filter whose BW is the data BW = 2Rs
No after correlator	-201.79	Note that No is the same before and after correlation but the BW is now the data BW instead of the spread
N at correlator output (dBW)	-168.78	Thermal noise power in data BW of 2Rs Hz
Peak signal PSD (dBW/Hz)	-180.97	Note that after despreading takes place in the correlator the PSD level increases by Gp = Rc/Rs
C/(N+I) at correlator output	5.32	Note that C/(N+I) increases by approximately the processing gain Gp = Rc/Rs
Effective C/(No+Io) (dB-Hz)	38.33	includes U/L and D/L thermal noise + CDMA multiple access interference
Implementation loss (dB)	-1.00	
Info Data Rate (bps)	1000.00	
Available Eb/(No+Io) (dB)	7.33	
Required Eb/No (dB)	4.5	10-6;QPSK; r=1/2 conv code
Link Margin at Hub (dB)	**2.83**	for single CDMA user