Figure 3-8 shows the minimum number of degrees that the temporary transceiver will off point from the geo-stationary arc assuming that the fixed BS is restricted to point within θ degrees of south. The graph is plotted for θ = 90, 80 and 70 degrees.

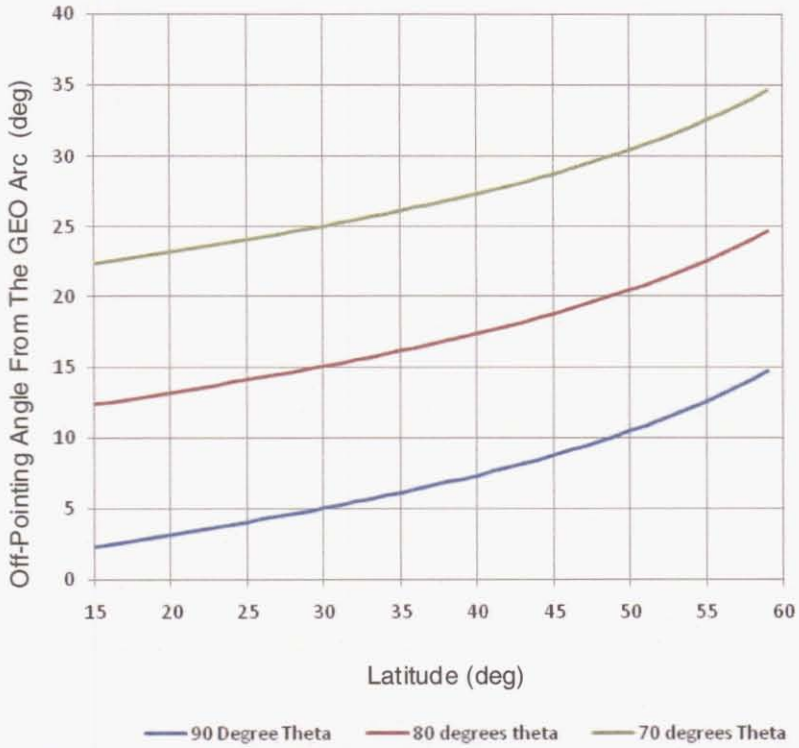

Figure 3-8 Temporary fixed receiver minimum angle from geo-stationary arc as a function of latitude

3.2.3 TFT Terminal

The TFT antennas were modeled according to ITU-R F.1245 (as the P2P antennas were). Since the TFT terminals transmit to the BS terminals, a BS terminal was placed at random within semicircles of radii 1, 3, 5, and 10 Km whose 180 degree arc center is pointing north. This prevent the TFT terminals from pointing southwards (i.e., towards the portion of the geo-stationary arc which is in line-of-sight). This is one method that the CII Coordinator can use to ensure that transmit terminals point at least 5 degrees from the geostationary arc.

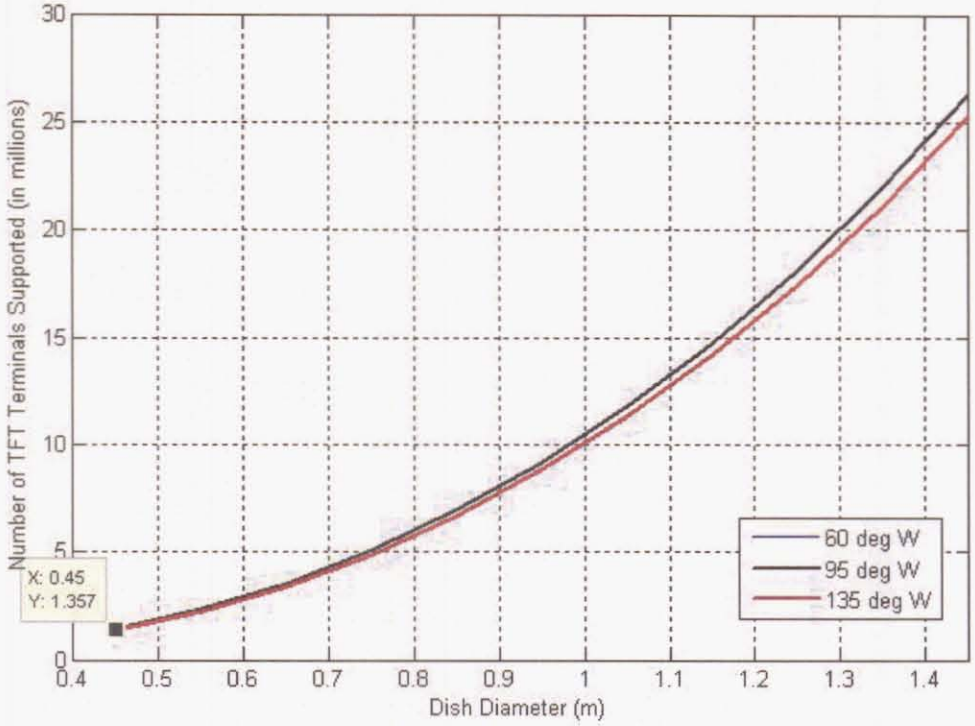

Figure 3-9. Maximum Number of TFT terminals that can operate simultaneously vs. antenna dish size assuming transmit power necessary to close the link. Blue and Red lines overlap, which is why the red line isn't as visible.

Simulations were performed to determine the maximum number of terminals that could operate simultaneously without exceeding the -12.2 I/N limit at the satellite. The results are depicted in Figure 3-9 as a function of the antenna dish size. The antenna gain of the satellite was assumed to be 31 dBi, which is typical for CONUS coverage. We note from this figure that even for the smallest dish size considered, the maximum number of TFT terminals which can transmit simultaneously is about 1.35 million.

The EIRP limit for P2P links was based on a 20 Km link in Florida, operating in a 99.999% fade condition, and using 45 cm receive and transmit antennas. A 10 Km P2MP link is equivalent in terms of required transmit power, when the BS has a 17 dBi gain, the TFT uses a 45 cm antenna and the link is in Florida in a 99.999% fade condition. Thus, a maximum EIRP equal to 45 dBW/50 Mhz will also be sufficient for the TFT terminals.

3.2.4 BS Terminal

The BS antennas were modeled by enveloping the ITU-R F.1336 radiation pattern assuming a minimum gain of 17dBi. Figure 3-10 shows the envelope antenna pattern. The height of the antenna is assumed to be 30m. These antennas are modeled as isotropic in azimuth and the gain varies with elevation angle. The bore sight of the antenna is

assumed to have a 0° elevation angle. This is a worst case assumption since terrestrial BS's typically downtilt their antennas to minimize inter-beam interference. Within the coverage area the BS antenna gain ranges from 17 dBi to about 14 dBi. The BS antenna gain towards receiving TFT terminals located within a 1km radius is less than 14dB, but this drawback is overcome because the path loss towards these locations is comparatively low with respect to the path loss at locations 10 Km away.

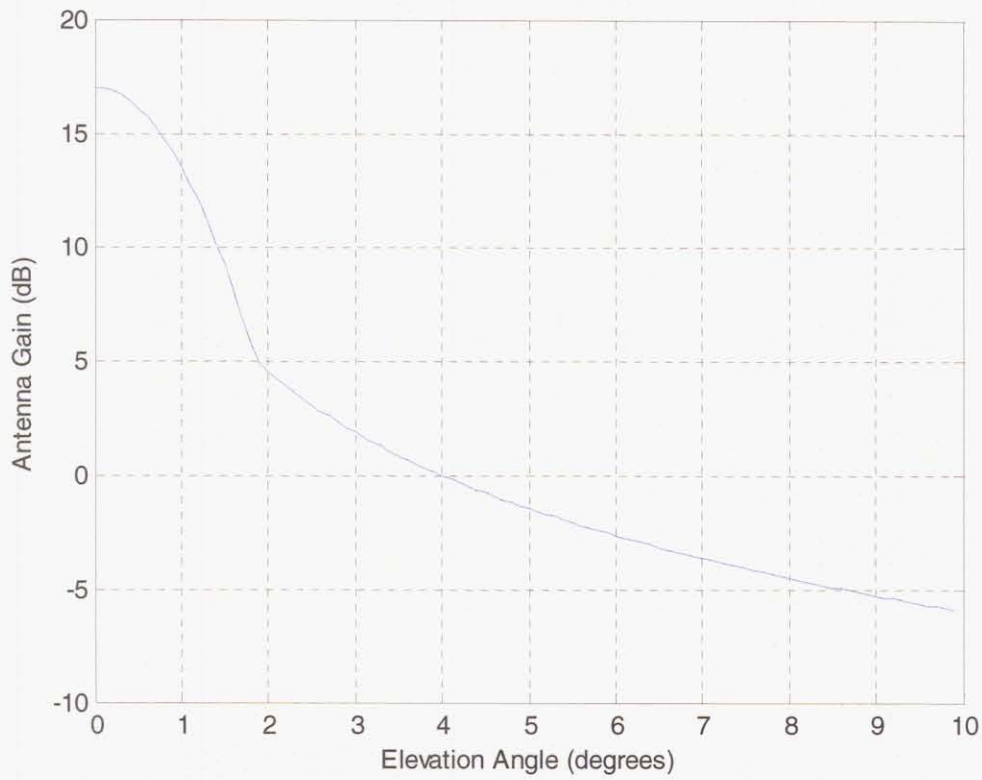

Figure 3-10. BS envelope radiation pattern of a linear array antenna based on model ITU F.1336. G_{max} = 17dB

A simulation was run to determine how many BS terminals can transmit simultaneously as a function of receiver dish size, given that TFTs are within 10km radius cells of the BSs. The gain of the satellite receive antenna was assumed to be 31dBi, which is typical. The results appear in Figure 3-11. We notice that even for a 0.45m TFT dish we can support 873,000 BS terminals.

Interference to the satellite increases as the BS antenna gain decreases. The proposed minimum BS gain is 17 dBi. A peak transmit power of 28 dBW would limit the transmit EIRP to 45 dBW when the BS gain is 17 dBi.

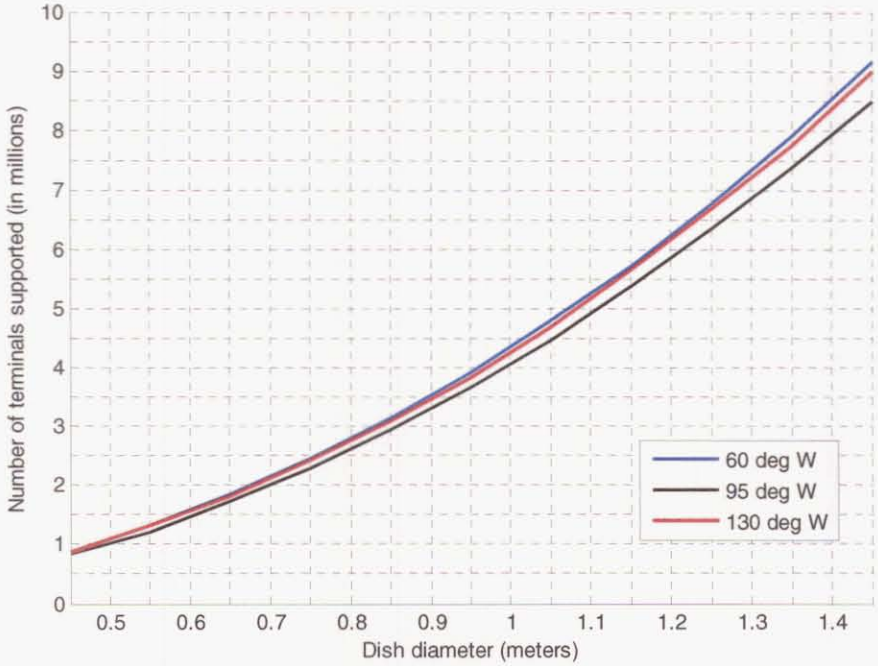

Figure 3-11. Maximum Number of BS Terminals Transmitting Simultaneously vs. receiver dish diameter, assuming transmit power which closes the average link in a 10km cell.

4. Mitigating Interference to the New CII Service

The CII Coordinator would work with the CII industry and individual users to recommend technologies and procedures available to mitigate interference to CII systems. Such techniques as best suited to individual circumstances would then be used by operators to protect themselves from VSATs, other CII stations, and other interference sources. This section describes some approaches for mitigating interference from satellite service transmitters into the new CII fixed service terminals. Such approaches include a technique for eliminating interference and coding desired signals through the portions of the band with high levels of interference.

Avoiding interference from the fixed satellite service transmitters (especially the VSAT terminals) into the new fixed service terminals is more challenging than avoiding harmful interference into the FSS satellites. Any harmful interference will likely be intermittent and over a relatively narrow bandwidth. Power levels for these uplink VSAT stations are on the order of one Watt, and their bandwidths will range from 1 MHz to 4MHz. Many VSAT transmissions are intermittent such as credit card acknowledgements from VSATs.

There are approximately a quarter of a million uplink VSAT stations operating in the 14.0 GHz to 14.5 GHz frequency band. Assuming that they are distributed roughly by population, then in an urban environment with a population of 70K per square mile there would be approximately six uplink VSATs in an urban square mile.

Figure 4-1 graphs the expected interference to noise ratio of a typical VSAT terminal with a 1MHz bandwidth and a 1Watt amplifier. The graph is provided in a log dB scale so that 10dB corresponds to the point where the interference is 10 times the background noise and at 20dB the interference is 100 times the background noise. If the I/N is 20dB then the transmitter would be required to transmit approximately 100 times the power for the same link quality. Notice that even at 20 kilometers away the interference is the same level as the noise, requiring the transmitter to transmit approximately double the power for the same link quality. The analysis assumed that the FS receiver and the FSS transmitter are in line of site from each other and that a 0dBi side lobe of the FSS VSAT transmitter is interfering with a 0dBi side lobe of the terrestrial receiver.

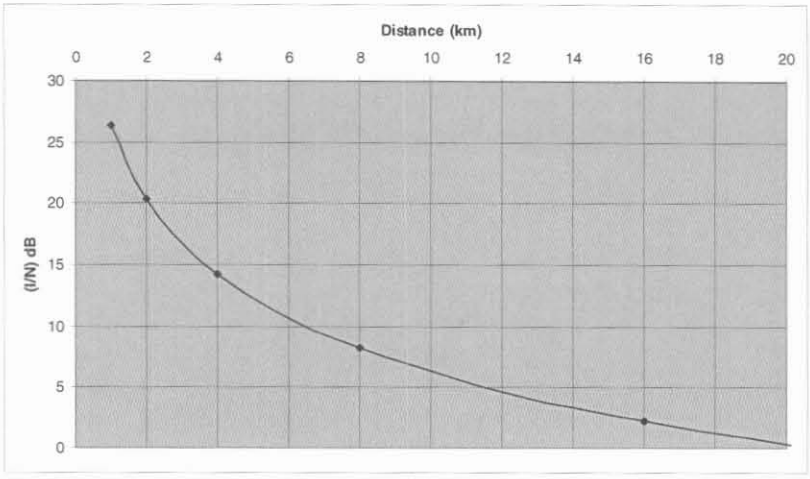

Figure 4-1: Interference from FSS VSAT station into the point to point FS sidelobe

The interference can be much larger if the VSAT is located within the main beam in line of site of the FS receiver. The chance of main beam interference is greater if the receiver uses a smaller dish. Figure 4-2 shows the interference level as a function of distance if the VSAT is in the main beam of a 45 cm antenna of the FS receiver. Notice that increasing the power of the FS link to overcome the interference will be impractical in many cases.

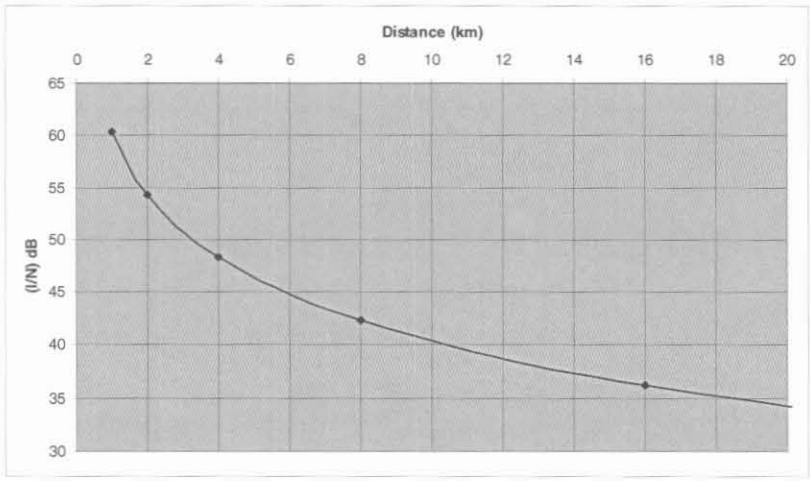

Figure 4-2: Interference from FSS VSAT station into point to point FS main beam

There are Mobile VSAT operators presently approved in this band (RaySat)[3] and others applying (e.g., GD)[4]. These interference sources will be unpredictable and can occur anywhere at any time. In order to mitigate this interference, FS receiver terminals must be able to quickly adapt to a dynamically changing interference environment.

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[3] *Raysat Antenna Systems, LLC*, 23 FCC Rcd 1985 (2008)

[4] *Amendment of Parts 2 and 25 of the Commission's Rules to Allocate Spectrum and Adopt Service Rules and Procedures to Govern the use of Vehicle-Mounted Earth Stations in the Certain Frequency Bands Allocated to the Fixed-Satellite Service, Notice of Proposed Rulemaking*, 22 FCC Rcd 9649 (2007).

Since this MSS usage is not implemented it is difficult to determine exactly how often the interference will occur. However, it is likely that the transmission characteristics are comparable to the fixed satellite service transmissions with similar interference effects.

a. Interference Mitigation Approach

The key to sharing in the crowded VSAT environment is to take advantage of the fact that the interference is narrowband. The proposed FS system would have a wide bandwidth allocation. The bandwidth would be at least 10 MHz to overcome the narrowband interference. Even in a crowded urban environment a large percentage of the bandwidth will have no interference.

Spread spectrum techniques are the obvious method for mitigating narrowband interference in the environment. Spread spectrum is defined here as any technique, which uses more bandwidth then required for signal transmission. Methods vary from direct sequence to frequency hopping.

A system based on Orthogonal Frequency Division Modulation (OFDM) may be an excellent candidate for this type of environment. OFDM has been well publicized as an approach for overcoming a multipath fading and interference environment by separating a high data rate signals into a parallel transmission of low data rate carriers as shown in Figure 4-3. This approach also divides the bandwidth into separate carriers that can be tested (using a limiter or blanker) for high levels of interference. Another advantage of OFDM is that its implementation can take advantage of Fast Fourier Transform (FFT) technology, a simple low complexity approach for high data rate applications. OFDM is becoming a popular standard waveform in wireless applications including LTE, WiMax, and WiFi.

The OFDM waveform does need to be optimized for the specific application. The performance will depend on the amount of bandwidth allocated to each operator and the FFT size. The allocated spectrum would is divided into sub-channels by the OFDM IFFT operation. The bandwidth of each sub-channel as a function of allocated spectrum is shown in Table 4-1.

Table 4-1: Allocated bandwidth versus sub-channel spacing

FFT Size	256	512	1024
Allocated Bandwidth (MHz)	Sub-channel bandwidth (KHz)		
10	39.0625	19.53125	9.765625
50	195.3125	97.65625	48.828125
100	390.625	195.3125	97.65625

These sub-channels are larger than is used by systems at lower frequencies to overcome multipath. The larger spacing makes the system less sensitive to phase noise and they are still narrow compared to the interference.

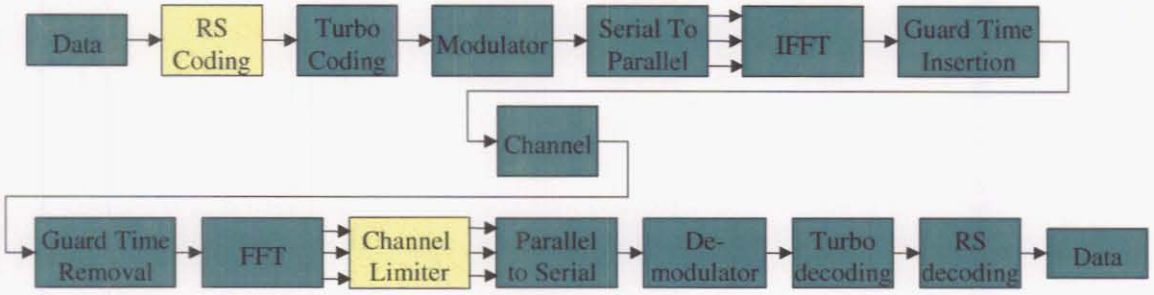

Figure 4-3: OFDMA system block diagram

In Figure 4-3 the transmitted signal is first Reed Solomon (RS) encoded such that each sub-channel is a RS symbol. The RS code protects against burst errors caused by narrowband interference. Concatenated with the RS code is a Turbo or low-density parity-check (LDPC) code for improved carrier-to-noise performance. At the receiver each sub-channel is soft-limited to remove high peak interference. The throughput and interference rejection capability of the system depend on the RS codeword chosen. The more overhead symbols that are used per packet, the greater the correction capability, but the lower the throughput.

Figure 4-4 demonstrates the correction capability versus the throughput, for several available bandwidths, of the OFDM system assuming 8 bit RS symbols, QPSK modulation and rate ¾ Turbo coding.

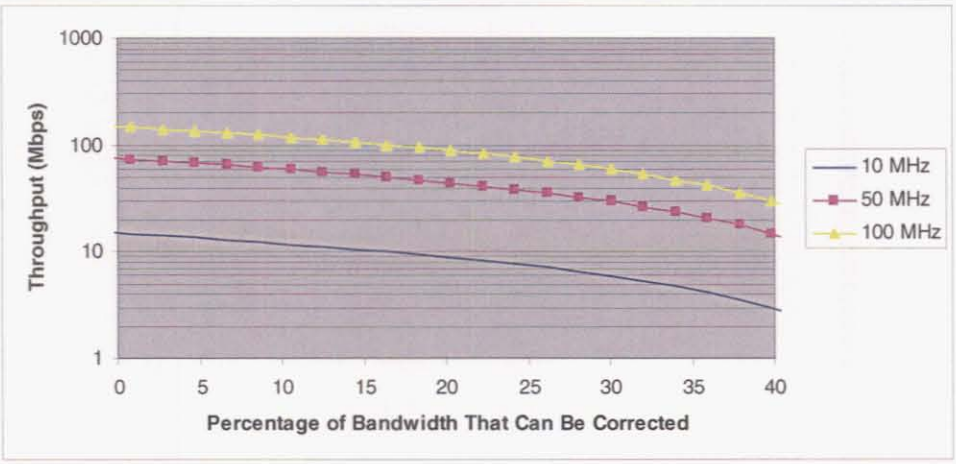

Figure4-4: Throughput for several channel bandwidths (10 MHz, 50 MHz and 100 MHz) versus the percentage of bandwidth that can be corrected

The OFDM implementation will differ depending on whether the terrestrial application is FS point-to-point or point-to-multipoint. In point-to-point applications the transmitter will use the entire allocated spectrum to transmit each RS codeword .

In point-to-multipoint applications all the users in the cell share the spectrum. Thus, if there are five users each can occupy 1/5 of the allocated spectrum. In this case each RS codeword would only be 39 symbols long with a corresponding reduction in throughput per user. In the forward direction the base stations multiplexes all the users such that their symbols are interleaved over the full allocated spectrum. This randomizes the errors per user. Correspondingly, in the return direction the user terminals are assigned non-contiguous carriers over the full allocated bandwidth.

b. Other Mitigation Approaches

The above approach, using OFDM, is effective and has relatively low complexity. The use of this modulation scheme along with other possible approaches discussed below can be combined for even higher reliability.

i. Active Interference mitigation

When the interference is high power and has a large duty cycle an active mitigation approach maybe appropriate. The received signal-to-noise ratio of each OFDM carrier is compared to a specified threshold to determine which OFDM carriers have interference. The receiver and transmitter coordinate so that no data is sent on carriers with interference. The receiver nulls those carriers with interference

ii. Automatic Repeat Queuing (ARQ)

Uncorrected codewords can be retransmitted improving Quality of Service (QOS) at the expense of throughput. ARQ can be optimized along with Forward Error Correction (FEC) to maximize the channel throughput for each environment.

iii. Power control

In cases of limited interference levels adaptive power control or equivalently adaptive coding and modulation can be used to overcome the interference. Figure 4-5 shows channel capacity versus the required carrier-to-noise ratio (C/Nreq). The dynamic range of the system shown is almost 10 dB from the lowest coding rate and modulation to the highest.

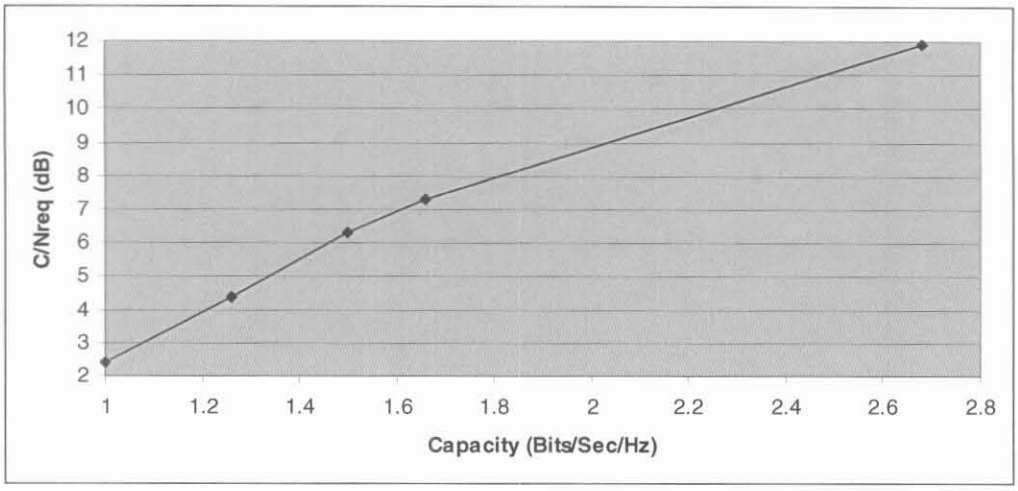

Figure 4-5: Channel capacity versus the required carrier-to-noise ratio

iv. Antenna nulling

Recently, smart antenna technology has gained wide interest commercially. Smart antenna technology has already been deployed commercially for applications such as mobile telephony and is becoming an integral part of all the wireless standards. It is possible for FS receivers to both sense and dynamically null out interference. In point-to-multipoint applications, base station antenna arrays (e.g. 4 antennas per sector) have been proposed that can null out multiple interfering sources. In point-to-point applications, multiple feeds can be configured on an antenna reflector. This approach can work effectively to mitigate single interferers that can arise at any time. The smart antenna technology will initially be more expensive but is expected to decrease in cost as users begin to make this technology standard.

With mobile terminal interference a more sophisticated system would be required to dynamically detect the presence of the interferer on a power density basis, and then to use the FS link antenna structure to dynamically form a null in the direction of the interferer.

The proposed dynamic system would use a spectrum analyzer (i.e., an FFT) to recognize the interference burst when it is present. The analyzer sweep rate (i.e., the FFT frame rate) would be set to sweep the assigned band rapidly compared to the duration of an interference burst in order to insure that the interference will be recognized on the first burst. In the case of a point-to-point microwave link, the receiving system will consist of a dual horn (one dimensional) mono-pulse receiver, with an FFT in each receiving path.

When a burst is recognized, the receiving system will generate a mono-pulse output voltage proportional to the arrival angle of the narrow FFT sub-channel containing the interfering burst. The receiving system then compares the angle output voltage to the mono-pulse calibration curve and sets the phase between the two receive horns to produce a null in the direction of the interferer. Extreme precision is not required in this nulling loop, as the system will pull more deeply into the null on successive FFT frames.

As an example, for as FS link bandwidth of 50 MHz, a 64 point FFT would partition this bandwidth into 780 KHz segments. Sampling this band-limited signal at 100 mega-samples/second, the frame time of the FFT would be 1/(1E8/64) = or 0.64 microseconds.

Each of the multiplies in the FFT would have to be performed in less than the FFT frame time of .64 microseconds, implying a clock speed for the multipliers of less than 10MHz. A receiving system with this set of parameters would easily recognize a burst having a 1-4 MHz bandwidth, and lasting several seconds. If the recognition threshold were set just above the nominal density level of the desired signal, this system would recognize an interferer ~16 dB below the total power of a desired signal occupying the full band.

This system of an ADC followed by an FFT and then an arithmetic combiner to form the mono-pulse error signal is relatively simple and could easily be realized in a Field Programmable Gate Array (FPGA) chip. Once the initial development was completed, these chips could then be produced for ~$1.00 each, and would not significantly contribute to the cost of the FS link.

v. LNA overload mitigation approach

If VSAT interference sources are too close to the receiver then it is possible to overload the FS receiver low noise amplifier. While this case should not occur often it is possible, so a possible LNA overload mitigation approach is presented. If a FS receiver were driven into overload by VSAT interfering signals, the resulting compression would both suppress the gain of the receiver for its desired signals, and would also generate intermodulation products that could directly interfere with the reception of the desired signals.

In combating the effects of overload from interfering signals, the proposed mitigating approach would be to first limit the bandwidth of the receive site through the use of filters. This would limit the signals that would reach the input stage of the receiver to only those that were within the assigned receiver's bandwidth. Second, if any interferer remained within the receiver's assigned bandwidth, it could be reduced to a level that would not cause overload by tuning a notch filter to the interfering frequency. These notch filters can have motor driven tuning screws, and be tuned remotely from a convenient console where the incoming spectrum is observed.

A typical FS receive site would consist of a receive antenna and associated receiver, where the receiver is modeled as an LNA followed by a down-converting mixer, an IF section, and then a demodulator. The mixer would typically have a Local Oscillator (LO) power of +15 dBm, and a conversion loss between 6 and 9 dB. The mixer would start to compress at an input level of ~ +5dBm. In order to have the overall input noise figure determined primarily by the noise figure of the LNA, the LNA gain would have to be ~10 dB higher than the losses that followed it. For this example the LNA gain could be set to 20dB. At 14 GHz, this would result in two LNA stages, with the first stage starting to compress at 0 dBm, and the second stage, (a slightly larger device with a somewhat higher noise figure), starting to compress at +10 dBm.

In reducing the overloading effects of large interfering signals, the first step would be to limit the input bandwidth of the receiver to its actual occupied bandwidth with a high Q cavity filter. For this case, an 8 pole elliptic-function filter with a 10 % guard band would have greater than 60 dB of attenuation.

For narrow band interferers within the usable pass-band, (e.g. occupying 1 MHz within a 50 MHz bandwidth) a tunable cavity notch filter could be employed to reduce their levels to well below the overload point of either the LNA or the following mixer. With realizable unloaded Qs of ~14000, the resulting inband loss (i.e. increase in system noise figure) would be under 1.0 dB.

In summary, the variety of ways that mitigation to FSS uplink station interference can be applied to the FS stations proposed in this band is clearly large. Any one of the options discussed, sometimes operating in tandem, can allow sharing with the large and growing number of FSS satellite uplinks.

5.0 Summary and Conclusions

The principal use of the 14.0-14.5 GHz band is presently reserved for uplink satellite services. This study has been concerned with the introduction of a Non-Governmental FS service for use by critical infrastructure operators.

It has been demonstrated in this study that a new FS service can be safely introduced to the band without causing harmful interference to either the primary satellite uplink users or the various secondary users which presently occupy the band.

It has also been shown that the new FS service, using modern digital signal processing advances and modulation schemes such as OFDM, can mitigate receiving interference from the band's current operators.

The study also demonstrates that a central CII coordinator is crucial to the process of ensuring spectrum sharing among CII operators and protecting other primary and secondary services that occupy the band.