expectation. No power control is implemented; the hub continuously transmits at full power. As in Figure 3-4, availability (degradation) is computed as a function of required C/(N+I) for 15 simultaneously active T1 rate Teledesic Standard Terminals for different geographic clustering factors. The performance of the TI system is comparable to the CellularVision system. At a C/(N+I) of 13 dB, the system availability is 99.83%, with degraded performance in the cells where FSS uplinks are clustered; system-wide performance is bounded by the performance with randomly located active uplinks. For a digital system such as this one, the signal quality is not as closely related to the C/(N+I). High quality video (or other information) is received for carrier-to-noise plus interference ratios of 13 dB or greater. As C/(N+I) decreases below 13 dB, the channel rapidly becomes unviewable (unintelligible), and lower C/(N+I) does not yield acceptable system performance.

Figure 3-6 shows the CellularVision and Texas Instruments hub-to-subscriber link performance as a function of TST sidelobe discrimination for a C/(N+I) threshold of 13 dB. Any slight performance difference is unrelated to the choice of modulation format. Figure 3-6 shows the difference between the two *systems*, **not** the difference between analog and

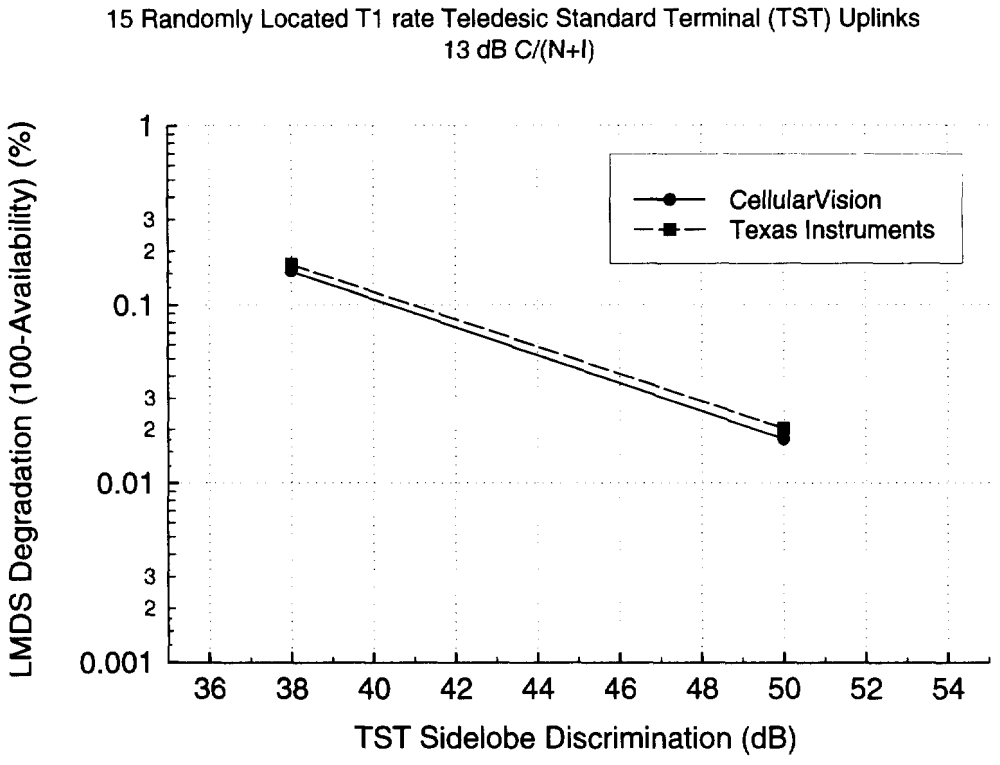


Figure 3-6. Performance of the hub-to-subscriber link of the CellularVision and Texas Instruments LMDS systems in the presence of interference from 15 simultaneously active T1 rate TST interferers as a function of TST sidelobe discrimination.

digital modulation. Figure 3-4, Figure 3-5, and Figure 3-6 indicate that LMDS availability of 99.9% can be achieved by a modest reduction in FSS sidelobe levels below the ITU mask level. The CellularVision availability can be increased by relaxing the definition of acceptable C/(N+I) to 11 dB. Decreasing FSS antenna sidelobe levels decreases the size of the area surrounding the uplink where interference is caused, producing a corresponding increase in LMDS availability. These calculations are based on *multiple* conservative assumptions regarding LMDS availability. Actual deployed LMDS availability will thus be greater than the availability calculated here. The conservative assumptions used in the computation of availability are described in detail in the following section.

3.5 Conservative Assumptions Used to Compute Availability

Multiple conservative assumptions were made in computing the LMDS availability. These assumptions were made to insure that the availability of actual LMDS systems will be greater than the computed values. Many of these assumptions are required because they model factors that are difficult to accurately quantify. Values that lead to the maximum amount of inter-system interference possible were used in the computation of LMDS availability. While these factors are difficult to quantify, estimates of the amount of improvement in LMDS system performance that will be realized in actual deployments can be made. The estimated availability improvements presented in Section 3.5.9 are conservative in that they estimate the minimum amount of improvement that can reasonably be expected under normal operating conditions. Considered individually, a particular assumption may or may not overestimate the interference (it will never underestimate) from a given FSS uplink to a particular LMDS receiver. However, when the aggregate of all possible interference cases and all of the conservative assumptions are considered, the statistical result is an LMDS system availability greater than the availabilities computed in this report.

3.5.1 Free Space Propagation

The analysis presented here of interference from FSS uplinks into LMDS receivers assumes free space propagation between all terminals. Blockage due to buildings or foliage is not included. It is appropriate for these calculations to represent the worst case since the presence of foliage cannot always be relied upon to eliminate interference. However, buildings and foliage will block some LMDS receivers from some FSS uplinks, effectively reducing the interference at those receiver locations. LMDS antennas may often be mounted on the sides of buildings, leading to an increased probability of blockage. Statistically, this results in real-world availability greater than the results presented here.

3.5.2 99.9% heavy rain 1% of the time

The calculations described here consider the 15 mm/hr heavy rain condition to exist 1% of all time. By definition, the 99.9% heavy rain condition exists only 0.1% of the time. Hence, the effect of increased interference under heavy rain conditions is included in the calculations ***ten times*** more often than will actually occur. Inclusion of the heavy rain case at 1% of the time instead of 0.1% of the time is more than sufficient to offset the effect of modeling as clear sky the varying amounts of light rain, which may be present up to 2% of

the time. In addition, non-Geosynchronous FSS uplinks transmit at maximum power less often when pointed at higher than the minimum elevation angle due to the decreased slant path rain attenuation. During periods of heavy rain greater than the 99.9% rain rate, the LMDS system may be unavailable due to the increased rain attenuation. During these periods, the presence of interference is inconsequential since the LMDS system is already unavailable. These assumptions for rain lead to actual availability greater than the results presented here.

3.5.3 LMDS Antenna

Performance of the LMDS hub-to-subscriber link is computed with the full azimuthal pattern of the subscriber antenna, including peak main beam gain. In nearly all cases, the LMDS subscriber antenna will have some elevation pattern discrimination in the direction of an interfering FSS uplink. This reduces the susceptibility of the receiver to interference due to the decreased antenna gain, statistically increasing the availability. The LMDS subscriber antenna mask was used to compute the worst-case interference levels at the receiver. There may be cases where the nulls of the LMDS subscriber antenna can be strategically pointed in the direction of an FSS uplink. This would dramatically increase availability for that user, particularly since the main beam of the LMDS antenna can be intentionally mispointed by up to 7 dB. The actual antenna pattern will have peaks and nulls that are *always* less than or equal to the level of the mask. Statistically, the difference between the mask and the actual antenna pattern increase the LMDS availability.

3.5.4 FSS Uplink Antenna

The FSS uplink antenna mask was used to compute the worst-case interference transmitted in the direction of LMDS receivers. The actual antenna pattern will have peaks and nulls that are *always* less than or equal to the level of the mask. For non-Geosynchronous satellite systems, the uplink antenna will have variable pointing as the satellite passes overhead. This randomizes over time the actual antenna sidelobe level in the direction of an LMDS receiver; the nulls in the pattern will sometimes be pointed toward the LMDS receiver. Even though the antenna mask does not require decreased sidelobe levels beyond elevation angles of approximately 40°, the actual antenna pattern will likely generally decrease as the angle from boresight increases. Occasional peaks at a small number of angles may be present, but will always be below the mask. For a geostationary FSS system, the antenna will remain at a fixed pointing angle, but the actual sidelobe levels will be below the mask. Although this decrease in sidelobe level is not always present, and cannot be reliably used to calculate interference, it does lead to a statistical decrease in interference and increase in LMDS availability relative to the levels calculated in this report. From Figure 3-6, even a 3 dB decrease in average sidelobe level would reduce periods of LMDS unavailability by nearly 50%.

3.5.5 Satellite Capacity

The availability calculations assume that a Teledesic satellite is operating at full capacity with 15 simultaneous T1 rate TST uplinks in a 53 km x 53 km square area. The actual number of simultaneously active terminals will almost always be less than the maximum

capacity. As with any telecommunications system, the maximum capacity is designed for a certain probability of blocking during the peak busy hour. Using Erlang theory for teletraffic, the average loading is only 9 T1 rate TSTs for 2% blocking during the peak busy hour. At periods of time other than the busy hour, the number of simultaneously active TSTs will be even lower. Even when the satellite is operating at near maximum capacity, there will be some variation in the number of simultaneously active terminals as links are initiated and terminated. Since there will be statistically fewer simultaneously active FSS uplinks than included in the calculations, the actual availability will be greater than the computed availability.

3.5.6 Full Spectrum Availability

The availability computed here in Chapter 3 is defined as the availability of the *entire* portion of the frequency band shared with the FSS uplink system. When interference does occur at a particular LMDS subscriber location, it will only occur in a limited number of LMDS channels. For a broadcast video LMDS system, this interference may occur in video channels that are not currently being viewed by a particular user. This increases the *perceived* availability. For a video distribution LMDS system, the busy hours for the FSS and LMDS systems are different, and the LMDS system availability will thus be greater than calculated due to the assumption of continuous operation at full satellite capacity during the non-busy hours of the FSS system. For a multiple access LMDS system, frequency reassignment techniques such as automatic link transfer, similar to handoff in cellular and PCS radio systems, can be used to avoid use of the channel suffering from localized interference. Loss of a small portion of the frequency band would temporarily decrease the local capacity of a single LMDS hub. This would not necessarily cause an outage for an LMDS subscriber potentially experiencing interference from an active FSS uplink transmission since this subscriber could operate on a different frequency as long as the LMDS system was not operating at full capacity. Implementation of the FSS/LMDS Spectrum Protocol described in Chapter 4 directs interference to different specific portions of the frequency band in each LMDS cell. This allows for decreased availability in a single channel while increasing the availability in the remaining channels.

3.5.7 Interference Spectral Density of Narrowband Interferers

The minimum required separation distances are computed with the interference level based upon the peak interference spectral density, rather than the total interference power in the receiver bandwidth. For interference with a narrower bandwidth than the desired LMDS signal, this results in an upper bound of the interference potential. Computations with the total interference power give the lower bound. The difference between the upper bound and lower bound of interference can be as large as 23.6 dB (16 kbps TST interfering with Texas Instruments LMDS). While the lower bound should not be used to compute the effect of the interference, the equivalent interference caused by a narrowband interferer lies somewhere in between the upper and lower bound. Hence, calculations with a narrowband interferer are conservative, overestimate the interference, and thus underestimate the availability. In addition, the C/(N+I) thresholds used to compute LMDS availability assume coincident center frequencies for the desired and interfering signals. Often, there

will be some frequency offset between the interfering and desired signals, resulting in an interference bandwidth narrower than the signal bandwidth. This leads to higher levels of tolerable interference for acceptable signal quality, increasing LMDS system availability.

3.5.8 Polarization

It is true that the NRMC calculations do not allow for any polarization discrimination in the calculation of interference from FSS uplinks into LMDS receivers. The far out sidelobes of a circularly polarized antenna are randomly elliptically polarized. This random elliptical polarization may coincide with the polarization of the LMDS receiver. Hence, it is appropriate that the sidelobe polarization not be included in the conservative computation of the required separation distance between a single FSS uplink and a particular LMDS receiver. However, the FSS sidelobe polarization in the direction of LMDS receivers is constantly changing as the antenna points in different directions to track the satellite flying overhead (non-GSO), and there are multiple LMDS receivers potentially affected by interference from a single FSS uplink. The random elliptical polarization will not always coincide with the polarization of each and every LMDS receiver. Statistically, there is some increase in availability due to the random polarization alignment (3 dB mismatch, on average) of the FSS uplink and LMDS receiver antennas.

3.5.9 Estimate of the Effect of Conservative Assumptions

By using conservative assumptions in the calculations, the actual availability of the LMDS systems will be greater than the computed availability. For each of the conservative assumptions listed above, an estimate can be made of the percentage of interference cases that would be eliminated due to the use of a more accurate (less conservative) assumption. For example, free space propagation is assumed for all interference paths between FSS uplinks and LMDS receivers. In actual system deployments, buildings will sometimes shield terminals from one another, eliminating the interference in many cases. Some signal paths are also affected, but this likely occurs much less often since the LMDS system is engineered to provide a stable path between the hub and subscriber. It is conservatively estimated that at least 15-30% of the interference cases will be eliminated due to attenuation of interference signals by buildings and foliage. Table 3-2 summarizes the estimates of the percentage of interference cases that will be eliminated by using more accurate models for all of the conservative assumptions in Sections 3.5.1 through 3.5.8. The improvements are estimated conservatively to accurately model the *minimum* LMDS system availability that can be expected in deployed areas. The cumulative improvement is computed by multiplicatively determining the percentage of interference cases that remain after taking into account all of the conservative assumptions.

Table 3-2. Summary of the estimated amount of conservatism in assumptions used to calculate LMDS availability.

Conservative Assumption	Estimated Availability Improvement	Justification
Free Space Propagation	15-30%	Blockage of interference will occur in some cases
Heavy Rain at 1%	20-30%	FSS uplink will often operate at reduced power
LMDS Antenna Mask	5-10%	Nulls in antenna pattern will sometimes be pointed in the direction of an FSS uplink
FSS Antenna Mask	10-15%	Nulls in antenna pattern will sometimes be pointed in the direction of LMDS receivers
Satellite at Full Capacity	30-50%	FSS System will not always operate at full capacity
Full Spectrum Availability	0%	Perceived improvement for some users; not included in estimate
Interference Spectral Density (upper and lower bound)	0-50%	No improvement for T1 rate TST into CellularVision video; potentially significant improvement for narrow band interferers
Polarization	0%	Statistical polarization mismatch does exist; effect accounted for in estimate of actual antenna patterns relative to the mask
Cumulative	60-90%	60-80% for wider bandwidth interferers

The curves for estimated availability are shown in Figure 3-7 for the LMDS systems studied here with interference from T1 rate Teledesic Standard Terminals. When the conservative estimates for real-world availability are taken into account, LMDS availability is significantly higher than the 99.9% availability for the CellularVision system at a C/(N+I) of 11 dB and the 99.83% availability for the Texas Instruments system at a C/(N+I) of 13 dB.

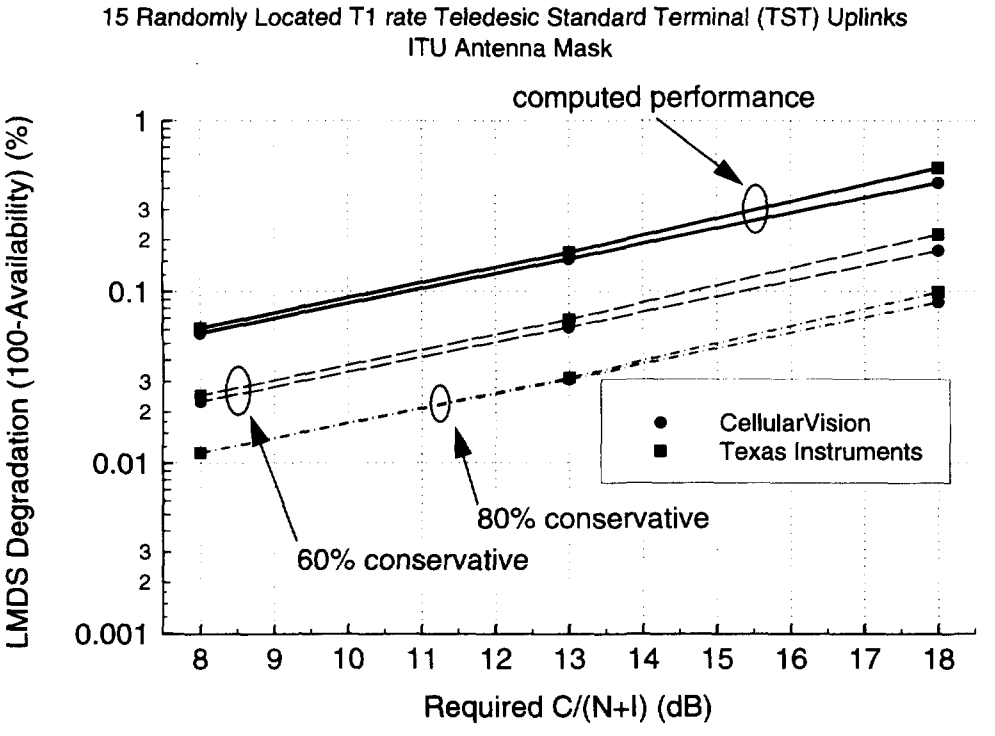


Figure 3-7. Estimate of the effect of conservative assumptions on the computed availability of LMDS systems in the presence of 15 simultaneously active T1 rate TST interferers for 60% and 80% cumulative conservatism.

3.6 Availability with 16 kbps TST Interferers

Instead of T1 rate traffic, up to 1440 16 kbps data rate TST uplinks can be simultaneously active in a 53 km by 53 km Teledesic "cell". While the small number of T1 rate users in an LMDS cell can be easily described by the binomial distribution, the binomial distribution for 1440 terminals becomes unwieldy, and it is impractical to simulate the LMDS performance in the presence of exactly *n* terminals where *n* ranges from 1 to 1440. Instead, multiple Monte Carlo simulations of random locations of 16 kbps FSS uplinks and LMDS receivers throughout a Teledesic "cell" were performed to provide an estimate of the LMDS system availability. These simulations provide "snapshots" of LMDS availability in the presence of interference. Multiple "snapshots" are averaged to estimate the availability. The performance of the CellularVision and Texas Instruments hub-to-subscriber links in the presence of interference from 1440 16 kbps Teledesic Standard Terminals is shown in Figure 3-8. Due to the much larger number of interferers at the 16 kbps rate and the use of the density of the interfering signal to compute the interference (upper bound), the computed LMDS system availability is reduced with 16 kbps interferers relative to the availability computed with T1 rate interferers. This occurs despite the reduced transmitter power of each of the lower rate uplinks. For the CellularVision system,

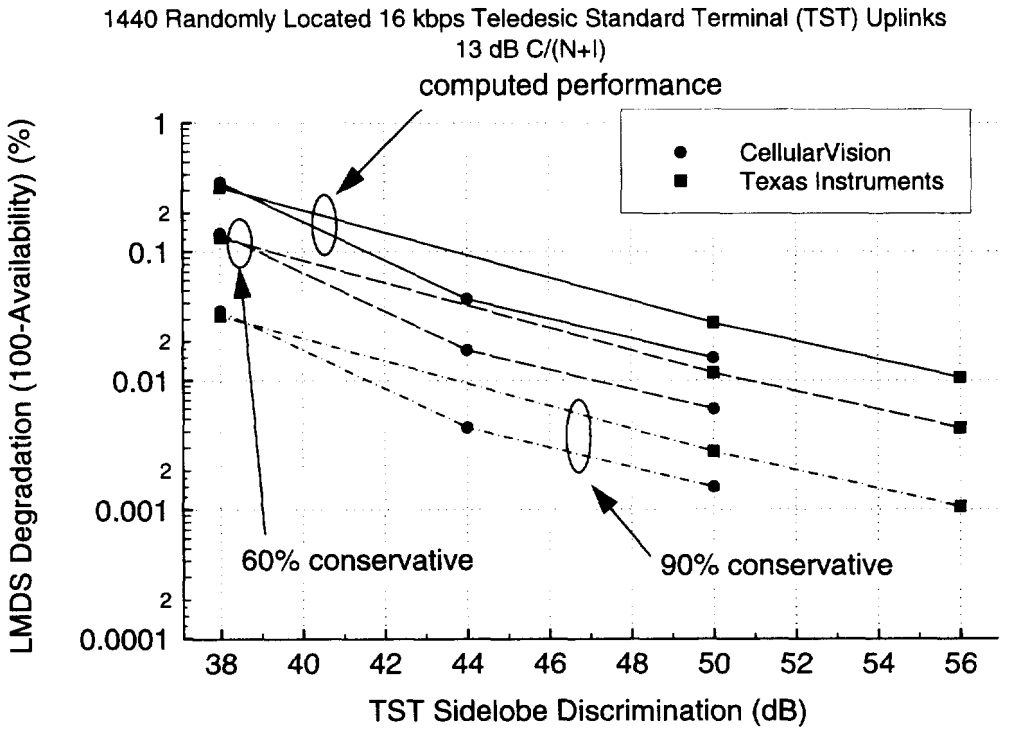


Figure 3-8. LMDS degradation (100-availability) at 13 dB C/(N+I) caused by interference from 1440 simultaneously active uniformly distributed 16 kbps TST uplinks in a 53 km by 53 km area.

the availability at 13 dB C/(N+I) is 99.65%. Although not indicated in the figure, a reduction in minimum C/(N+I) to 8 dB yields an availability of 99.9% before the conservative assumptions are considered. The Texas Instruments system achieves an availability of 99.7% The impact of 99.7% availability on a digital system with forward error correction is different than the impact on an analog system, and availability of 99.7% may be acceptable to digital LMDS service providers. Further LMDS system improvements can also be used to achieve higher availabilities. With the improvement that will occur due to the conservative nature of the assumptions, including the effect of the interference spectral density bound, availability in excess of 99.9% is achieved for both systems at a C/(N+I) of 13 dB. The spectrum protocol described in Chapter 4 improves the LMDS system availability to 99.9% at 13 dB C/(N+I) *without* the conservative assumption improvement.

3.7 Availability with T1 rate SPACEWAY Interferers

The availability calculations presented previously are for Teledesic Standard Terminal FSS uplinks interfering with CellularVision and Texas Instruments subscriber LMDS receivers. LMDS availability is lowest in the presence of Teledesic Standard Terminals for several reasons. First, the density of simultaneously active T1 rate uplinks over a geographical area is greater in the Teledesic system than in the SPACEWAY system. In a single 53 km x 53

km Teledesic cell, 15 T1 rate uplinks can be simultaneously active for a density of one active uplink every 187.3 square kilometers. In the SPACEWAY system, 60 simultaneous T1 rate uplinks can be accommodated in a 650 km diameter spot beam for a density of one active uplink every 5,530 square kilometers. Multiple spot beams in the same geographic area would yield a higher density, but 30 spot beams in exactly the same geographic area would be required to achieve the same density of simultaneously active T1 rate uplinks as the Teledesic system. This is many times more than specified in the SPACEWAY system design [1]. The second reason that the Teledesic system represents the worst case availability is because of the overlap of the requested portion of the frequency band and the relative bandwidths of the FSS uplink signals. The SPACEWAY system has requested use of the 29.0-30.0 GHz portion of the frequency band. This band only partially overlaps the LMDS band B allocation of 28.5-29.5 GHz. To avoid interference into LMDS receivers, a SPACEWAY uplink should *whenever possible,* operate in the 29.5-30.0 GHz portion of the band when in the vicinity of LMDS receivers. When operating in the 29.0-29.5 GHz portion of the band, the SPACEWAY uplinks should transmit in the frequency gaps between LMDS hub-to-subscriber link transmissions. These techniques are discussed further in Chapter 4 describing the FSS/LMDS Spectrum Protocol. Implementation of the spectrum protocol will yield LMDS availabilities well in excess of 99.9% in the presence of SPACEWAY uplinks.

3.8 Chapter Summary

This Chapter has presented the results of availability calculations of LMDS hub-to-subscriber links in the presence of interference from FSS uplinks. The development of the methodology for computing LMDS system availability due to degraded signal quality from interference caused by FSS uplinks based on the system usage descriptions provided to the NRMC is the second major step towards achieving an FSS/LMDS co-frequency sharing solution. Due to the limited density of simultaneously active FSS uplink terminals, the availability of the LMDS systems studied can be greater than 99.9% when Teledesic Standard Terminal FSS uplinks operate with the ITU antenna mask, even though required minimum separation distances to avoid interference can be as large as several kilometers in some situations. This is achieved by modifying LMDS system designs to improve their tolerance to interference from FSS uplinks operating in the same geographic area. Further work in the LMDS community is continuing to improve LMDS system designs so that FSS and LMDS can co-exist in the 28 GHz band. Multiple conservative assumptions have been made in the calculations that indicate the real-world availability will be greater than the values computed here. The CellularVision system achieves 99.9% availability by increasing the hub transmitter power, implementing an improved antenna mask, and allowing for a slightly degraded picture quality at a C/(N+I) of 11 dB. The Texas Instruments digital data LMDS system achieves an availability of 99.7% at a C/(N+I) of 13 dB. The impact of 99.7% availability on a digital system with forward error correction is different than the impact on an analog system. Implementation of FSS antennas with improved sidelobes will increase the LMDS system availability to greater than 99.9% at a C/(N+I) of 13 dB and decrease the size of the areas where interference occurs. In Chapter 4, an FSS/LMDS Spectrum Protocol is described to limit the number of harmful co-frequency interference exposures between FSS uplinks and LMDS receivers and further improve the availability of LMDS systems.

4. FSS/LMDS Spectrum Protocol

4.1 Overview

Based on the description of future FSS systems submitted to the 28 GHz FSS/LMDS NRMC, a single FSS uplink can cause interference to LMDS receivers over bandwidths of 275 kHz to 26.4 MHz (800 MHz TGT excluded). The portion of the frequency band shared between any one FSS and LMDS service provider is at least 400 MHz wide. For a broadcast FM video LMDS system, the shared 400 MHz is channelized into 20 MHz channels with an occupied bandwidth of 18 MHz per channel. Gaps in the broadcast downstream frequency spectrum of 2 MHz between adjacent channels thus exist. The FSS/LMDS Spectrum Protocol is a novel method developed by Bellcore to direct the narrowband FSS uplink traffic into these downstream frequency gaps so that the number of co-frequency interference exposures to LMDS subscriber receivers is reduced. In addition to the frequency gaps between channels, an ordered list of frequencies (or groups of frequencies corresponding to LMDS channels) in each LMDS cell will be determined by the LMDS provider for sequential use by FSS uplinks located in that cell. In this manner, the interference, when it occurs, is directed to a specific channel (or small number of channels) in the LMDS channel plan. The availability for this channel is then lower than the availability of the remaining channels, and the LMDS service provider can decide whether or not to offer program material in this channel. If the frequency of this channel is different in different LMDS cells within the satellite "cell", multiple FSS uplinks in different LMDS cells can transmit in the frequencies corresponding these reduced availability channels. This is possible even when the full satellite bandwidth is being used, depending upon the geographic distribution of FSS uplinks. Both FSS and LMDS systems have simultaneous access to the entire frequency band everywhere. This is NOT a band segmentation protocol. It is shown later that the spectrum protocol improves the system availability to greater than 99.9% for LMDS systems without changing FSS antenna sidelobe levels. Implementation of the FSS/LMDS Spectrum Protocol is the third major step towards achieving a co-frequency sharing solution.

The Teledesic Gigalink Terminal (TGT) uses a bandwidth of 800 MHz, making it impossible to develop a suitable spectrum protocol. Since there will be relatively few Gigalink Terminals, the locations of these terminals can be determined via traditional methods of frequency coordination to insure that harmful interference is not caused into existing LMDS receivers. Coordination to determine the location of TGTs will also be required with users in the 18 GHz band to insure that the satellite downlink does not cause harmful interference.

4.2 Detailed Description

4.2.1 CellularVision Broadcast Video LMDS System

Consider a broadcast video distribution LMDS system as described by CellularVision to the NRMC. LMDS hub transmissions are channelized into 20 MHz channels with an occupied bandwidth of 18 MHz. In the guard band between adjacent channels, there is a 2 MHz portion of unused downlink spectrum. FSS uplinks operating with a bandwidth of 2

MHz or less could transmit in these frequency gaps without causing harmful interference to LMDS subscriber receivers. Some LMDS systems will implement frequency interleaving between rows of adjacent cells. With frequency interleaving, there will be two sets of frequency gaps available across the LMDS deployment. Figure 4-1 shows one possible frequency interleaving and reduced availability channel assignment for an LMDS deployment. Channel sets A and B are frequency interleaved; frequency gaps in channel set A are interleaved with those in channel set B. Narrow band FSS uplinks search an ordered list of the frequency gaps in the LMDS cell where the uplink is located for an available frequency. The uplink continues to search the list until a frequency is found that is not currently in use by other uplinks accessing the satellite receiver. In addition to the gaps between adjacent LMDS channels, the LMDS service provider will specify an ordered list

1A	2A	3A	4A	5A	6A	7A	8A
11B	12B	13B	14B	15B	16B	17B	18B
9A	10A	11A	12A	13A	14A	15A	16A
19B	20B	1B	2B	3B	4B	5B	6B
17A	18A	19A	20A	1A	2A	3A	4A
7B	8B	9B	10B	11B	12B	13B	14B
5A	6A	7A	8A	9A	10A	11A	12A
15B	16B	17B	18B	19B	20B	21B	22B

Figure 4-1. One possible frequency interleaving and LMDS video single channel reduced availability plan for an FSS/LMDS spectrum protocol throughout a multi-cell coverage area that coincides with an FSS footprint or subset of a footprint. Channel sets A and B are frequency interleaved and the channel number represents the set of frequencies that an FSS uplink located in that cell would use first after exhausting the guard bands used in that cell. FSS uplinks are never prohibited from transmitting on any given frequency, provided that the guidelines of the protocol are followed.

of frequencies (or frequency blocks) for each LMDS cell for use by FSS uplinks operating in that cell. The ordered frequency list contains the entire shared frequency band so that there is no capacity penalty for the FSS network. Hence, frequencies on the list coincide with operational LMDS hub-to-subscriber link channels. The group of frequencies at the start of the list corresponds to a single LMDS channel. This channel would thus be the first LMDS channel to encounter harmful interference. The signal quality of this channel would be lower than in the other channels. By sacrificing some availability in a single channel, the availability of the remaining channels is shown later to increase to greater than 99.9%. The ordered list of frequencies corresponds to the allowable carrier frequencies as specified in FSS system designs. The LMDS channel specified to have the lowest availability can carry the same program material (or no program material) in all LMDS cells, but is a different RF frequency slot in different cells. For 400 MHz of shared spectrum between an LMDS band B service provider and a Teledesic FSS service provider, a frequency reuse plan of 20 could be used as shown in Figure 4-1. Two different channel plans are shown in Figure 4-1 due to the frequency interleaved channel plans. The frequency reuse of 20 is only for the selection of which LMDS channel is the first to be interfered with. The LMDS system reuses the entire frequency band in each cell.

From the satellite viewpoint, the full allocated bandwidth is available everywhere for uplink transmissions (even if all transmissions are in the same LMDS cell), and there is NO capacity penalty for implementing this spectrum protocol as uplinks are NEVER prohibited from transmitting on any given frequency. Likewise, the LMDS system uses the entire frequency band in each cell, with reduced availability in a single channel. Compliance with the spectrum protocol makes the FSS uplink a "good neighbor" by directing the potential interference to specified portions of the frequency band, reducing the likelihood of co-frequency operation with nearby LMDS receivers. Compliance permits LMDS service providers to effectively design their systems and tailor their service offerings to deal with the occasional received interference. The spectrum protocol for an FSS uplink searching for a channel to access is summarized in the flow chart in Figure 4-2.

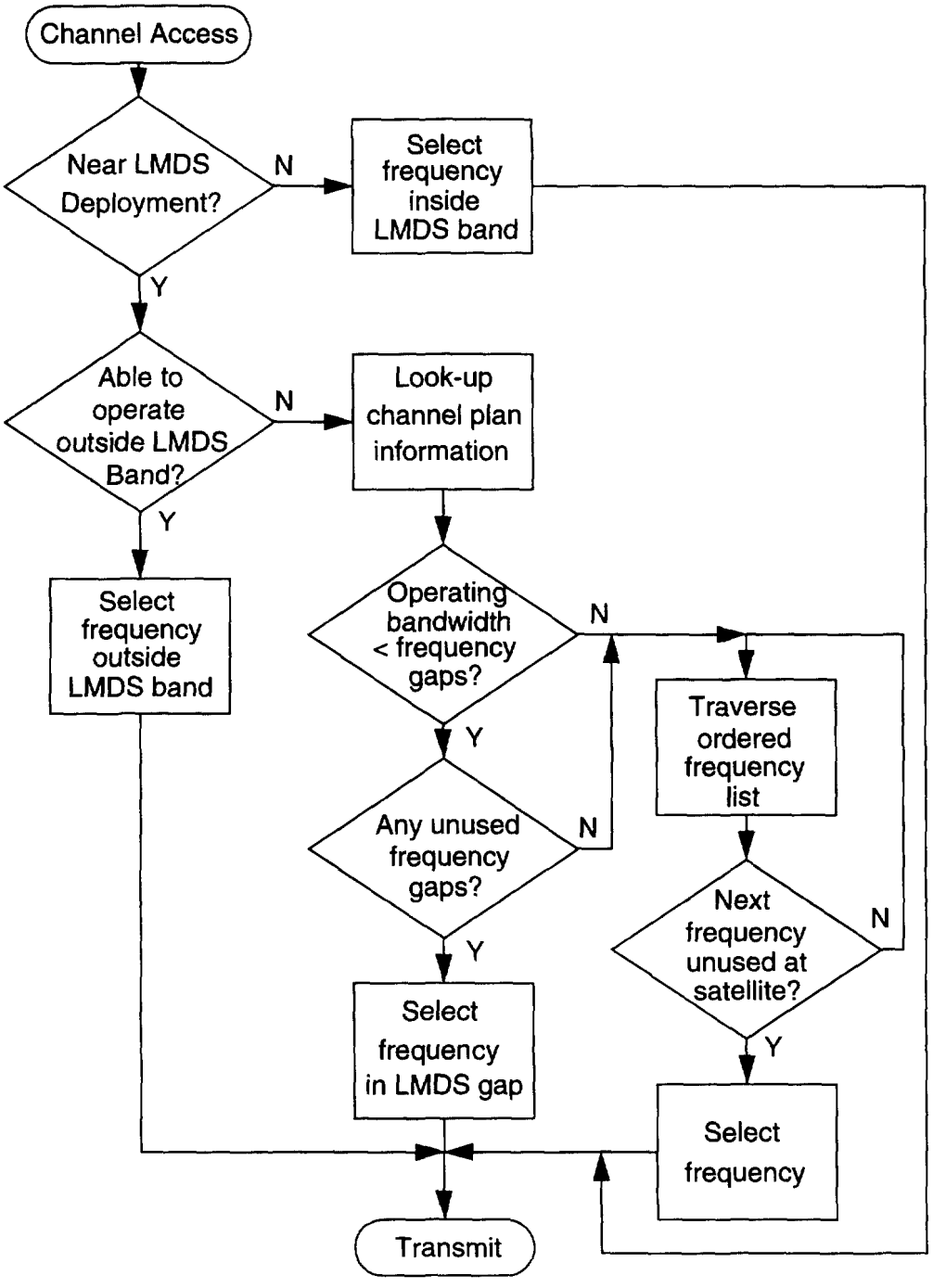


Figure 4-2. Flowchart of FSS/LMDS Spectrum Protocol for FSS uplink channel access.

4.2.1.1 Interference From 16 kbps Teledesic Standard Terminals

Teledesic Standard Terminal uplinks require a contiguous allocated bandwidth of 275 kHz for each 16 kbps user. This gives 7 available frequency slots in each 2 MHz frequency gap between adjacent channels. There are 19 such frequency gaps in each frequency interleaved channel set. Selecting one video channel as the first one to receive harmful interference gives an additional 16 MHz in each cell. Although each video channel occupies 18 MHz, the 2 MHz at the center of the channel has already been prioritized for use in cells with the opposite frequency interleaving scheme. This gives an additional 57 frequency slots for a 16 kbps uplink to use before causing harmful interference in that cell to channels other than the single reduced availability channel. When the spectrum protocol is implemented, degradation on the single reduced availability LMDS channel in each cell is considered NOT to be harmful; availability is computed for the remaining channels. Figure 4-3 shows an example of how the spectrum protocol would be used for a narrowband uplink in a single LMDS cell. When initiating a call, the uplink traverses a list of possible channel frequencies until a channel unused by other FSS uplinks is found. The channels in the frequency gaps of the LMDS broadcast spectrum are at the beginning of the list, and the frequencies corresponding to a single video channel (different from cell to cell) are next.

4.2.1.2 Interference From T1 Rate Teledesic Standard Terminals

A T1 rate TST uplink occupies a contiguous bandwidth of 26.4 MHz. This roughly corresponds to a single LMDS video channel. While there will be some additional degradation of adjacent LMDS video channels, the extent of this degradation will be limited since with only partially overlapping bandwidths, a lower level of C/I may be tolerated. With this spectrum protocol, essentially the first T1 rate TST uplink in each LMDS cell does not cause harmful interference outside the single reduced availability channel. Harmful interference will occur only when multiple uplinks in the same LMDS cell are simultaneously active. Hence, the improvement in LMDS availability decreases when simultaneously active FSS uplinks are clustered in a small geographic region. The resultant system availability is upper bounded by the availability computed when a uniform distribution of FSS uplinks is present, and no spectrum protocol is used (see Figure 3-4).

4.2.1.3 Interference From SPACEWAY Uplinks

The requested frequency allocation for SPACEWAY is 29.0-30.0 GHz, which only partially overlaps the LMDS band B of 28.5-29.5 GHz. SPACEWAY uplinks operating in areas where LMDS receivers are present should first operate in the 29.5-30.0 GHz band whenever possible. When the entire 29.5-30.0 GHz band is in use by other FSS uplinks (in that spot beam), the FSS uplinks should operate in one of the remaining 24 2 MHz frequency gaps in the 29.0-29.5 GHz LMDS broadcast spectrum. With frequency interleaving, there are two groups of 24 frequency gaps that are available in any area where LMDS and SPACEWAY uplinks coexist. SPACEWAY uplinks that operate in regions where there are no LMDS receivers should transmit in the 29.0-29.5 GHz portion of the frequency band so that they do not use up the available capacity for uplinks operating in areas where LMDS is deployed. The combination of sparsely located SPACEWAY uplinks with the implementation of this spectrum protocol should lead to LMDS system availability

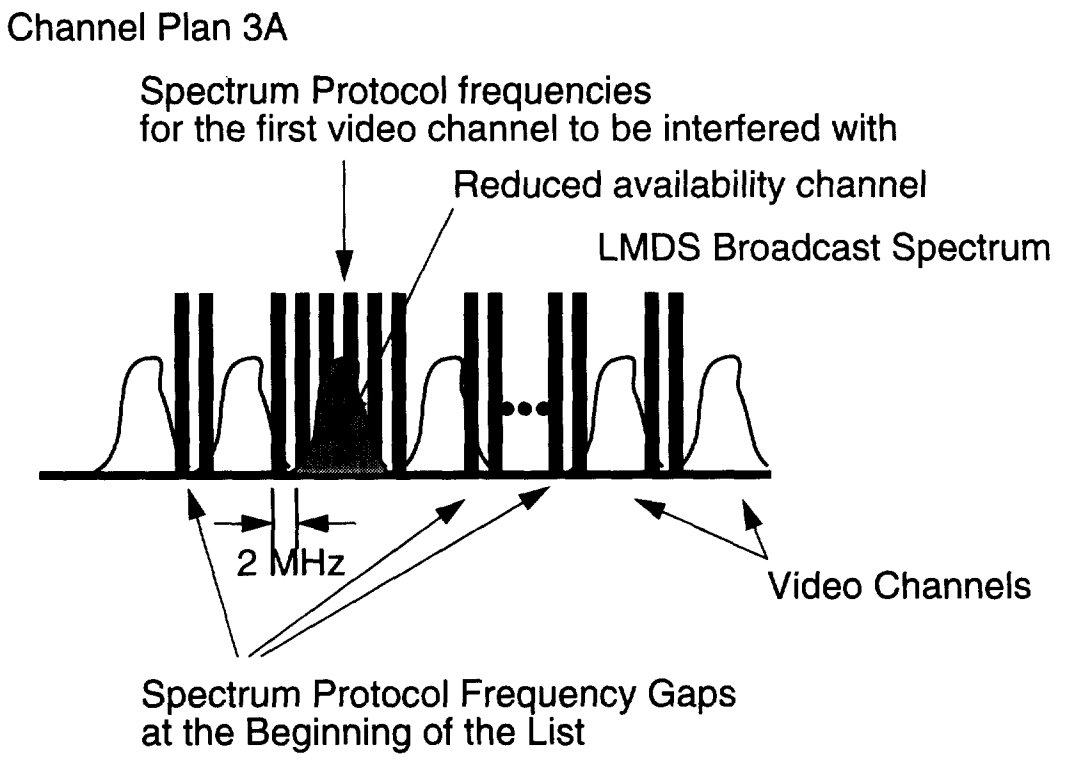


Figure 4-3. Spectrum protocol for a 16 kbps TST located in an LMDS cell. The uplink traverses a list of possible channel frequencies until an unused channel is found. The channels in the frequency gaps of the LMDS broadcast spectrum are at the beginning of the list, and the frequencies corresponding to a single reduced availability video channel are next.

well in excess of 99.9%. Multiple SPACEWAY uplinks operating at 1/2 or 1/4 T1 rate can fit in the gaps between LMDS channels. Hence, implementation of the spectrum protocol described here effectively provides LMDS system availability greater than 99.9%.

4.2.2 Digital Data Multiple Access LMDS Systems

Consider a digital data LMDS system such as the one described by Texas Instruments to the NRMC with 52 Mbps channel bandwidths with a flexible service offering of video, data, and telephony. The allocated spectrum is divided into uplink and downlink segments. Traffic usage is not broadcast, but is multiple access as LMDS subscribers initiate and terminate communications with the hub. Hence, all channels are not used all the time since the system would be designed for peak capacity during the busy hour with some specified probability of blocking. FSS uplinks would transmit on an ordered list of frequencies that is specific to the LMDS cell where the FSS uplink is located. Selection of which portion of the spectrum to interfere with first would be different in each LMDS cell such that multiple FSS uplinks could transmit before causing harmful interference in other than the single specified reduced availability channel in each LMDS cell. A "channel packing" scheme can

be used to reduce the likelihood of simultaneous co-frequency operation by both FSS and LMDS systems in the same geographic area. Figure 4-4 shows a channel packing scheme where the LMDS subscribers would start at the lower end of the band and continue to search upwards until a channel unused at the hub was found. FSS uplinks operating in the LMDS cell would start at the top of the band and continue to search downwards until a channel unused at the satellite was found. Channel packing is one way of viewing the spectrum protocol presented here, except that instead of traversing the frequency band from one end to the other to find an unused channel, an FSS uplink would traverse the list of ordered frequencies where the ordered frequency list is specified by the LMDS service provider to minimize the number of co-frequency interference exposures that LMDS receivers are subjected to. The packing of the channels is determined by the ordered frequency list.

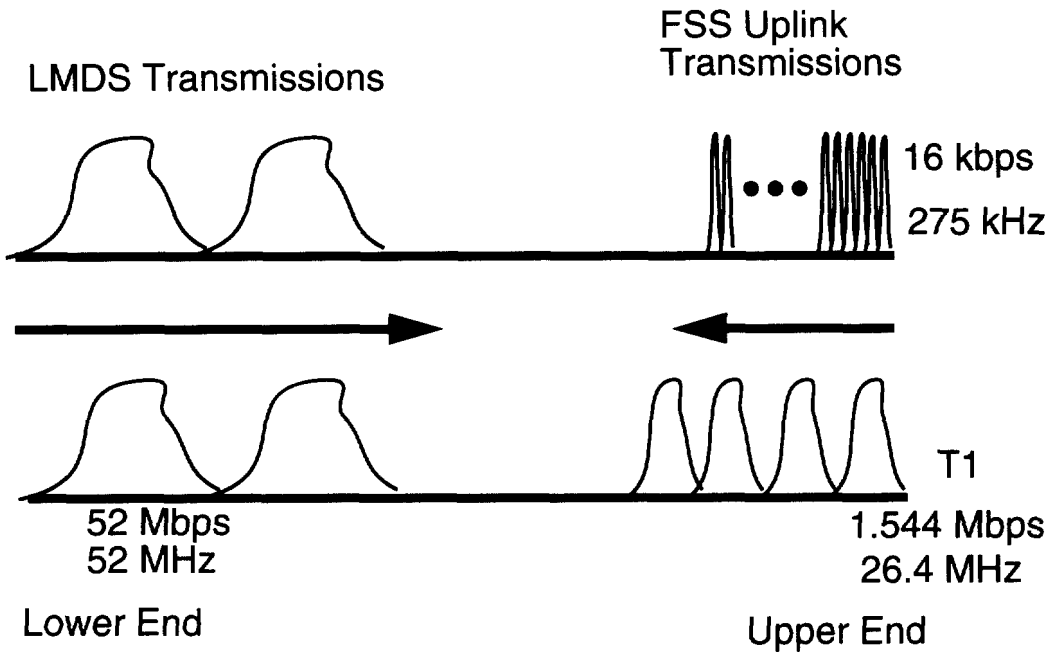


Figure 4-4. Example of a channel packing scheme for a multiple access LMDS system to reduce the number of LMDS receiver co-frequency interference exposures from FSS uplinks. The numbers given in the example are for a TI LMDS system and a Teledesic Standard Terminal operating at either 16 kbps or 1.544 Mbps (T1 rate).

4.2.2.1 Interference From Teledesic Standard Terminals

Consider a single 52 MHz segment of spectrum for the TI digital data multiple access LMDS system. In 52 MHz, 189 16 kbps users (275 kHz each) could be simultaneously active in a single LMDS cell before more than one LMDS channel would be potentially interfered with. Nearly two T1 rate TST uplinks fit in the bandwidth of a single LMDS

channel. Hence, with the spectrum protocol, up to the first two T1 rate TST uplinks in each LMDS cell would not cause harmful interference on frequencies other than the reduced availability channel. The availability for the TI system with FSS uplinks using the protocol is computed for 348 of 400 MHz where a single 52 MHz channel in each cell accepts reduced availability. The same 52 MHz portion of the spectrum will be at the beginning of the ordered frequency list every eighth LMDS cell (8 possible channel sets). This has been included in the calculation of LMDS system availability. It is assumed that all channels support hub-to-subscriber downlink traffic. No frequency gaps are assumed since this information was not specified in the NRMC system description. Specification of frequency gaps for FSS transmissions would improve the actual performance relative to the values computed here. For a multiple access LMDS system, the only time the system will encounter *any* inter-system interference is when combined use of the shared spectrum in a single LMDS cell exceeds the total 400 MHz (overlap). That is, even though calculations show interference in the "second" LMDS channel, that channel may not be in use due to LMDS system demand. The "second" channel is the second of eight possible channels to be interfered with. This channel is the "seventh" channel to be used by LMDS in that cell. If the LMDS hub has six or fewer channels in use, interference in the "seventh" channel does not cause the LMDS system to be unavailable. Furthermore, a channel that is calculated as receiving harmful interference may actually be in use as a return link, depending on the channel plan of the LMDS system. The effect of the spectrum protocol on return link traffic is discussed further in Section 4.2.3.

Determination of whether the ordered frequencies at the beginning of the list for a given LMDS cell correspond to downstream or return link traffic is left to the discretion of the LMDS service provider. The goals of this work were not to investigate the most efficient implementations of the spectrum protocol, but to determine the framework of the spectrum protocol and investigate the performance improvement possible when the protocol is implemented under conservative assumptions. This is the minimum amount of information required to develop flexible rules for spectrum usage that achieve co-frequency sharing. More efficient implementation of the protocol may exist. In addition, other LMDS architectures and service offerings may need to be studied in detail to determine the appropriate implementation of the protocol and the resultant system availability. Further information from both the FSS and LMDS proponents describing call set-up, traffic distributions, and dynamic frequency assignment is required to perform more detailed simulations. This would allow the determination of optimum spectrum protocol implementation and more precise computation of resultant LMDS availability.

4.2.2.2 Interference From SPACEWAY Uplinks

In a single 52 MHz segment of spectrum, 26 T1 rate SPACEWAY uplinks could be accommodated in each cell. With SPACEWAY uplinks located in the same geographic areas as LMDS systems and operating in the 29.5-30.0 GHz band before operating in the shared 29.0-29.5 GHz band, the occurrence of interference from these uplinks will be extremely rare, resulting in availability in excess of 99.9%.

4.2.3 Impact on LMDS Subscriber-to-Hub Return Links

Implementation of the spectrum protocol may or may not affect LMDS subscriber-to-hub return links depending upon the LMDS frequency plan. The LMDS service provider has the option to tailor the implementation of the protocol to most efficiently meet the system performance objectives. For implementations of the FSS/LMDS Spectrum Protocol that specify the LMDS return link spectrum at the beginning of the ordered frequency list, the availability of LMDS return link channels becomes an issue. For all LMDS systems, the return link is a multiple access channel. Hence, the occurrence of interference effectively reduces the capacity of the LMDS return links. Return link capacity can be traded for downlink LMDS availability. Some portion of the allocated LMDS bandwidth outside the portion shared with FSS could be reserved for return link traffic, to insure some minimum amount of return link capacity. With the potential for interference on these return links in shared spectrum, some method of frequency assignment similar to automatic link transfer (ALT) or handoff used in cellular and PCS radio systems will need to be developed to prevent dropped "calls" due to the presence on interference on a given channel. This increases the complexity of the LMDS system design. The use of interference cancellers at hub receivers is another option, but is an option that would significantly increase the system complexity.

Each hub receiver has an interference zone around it determined from the calculation for the minimum required separation distance. If an FSS uplink is located in this interference zone, it could cause interference to the hub receiver. One method of protecting the hub receiver would be to implement the ordered channel list such that FSS uplinks close to the hub operate on a frequency corresponding to one of the LMDS downlink channels (e.g., the single reduced availability channel). This is the same as what happens when FSS uplink transmissions occupy wider bandwidth than LMDS return link channels. By tailoring the implementation of the spectrum protocol for uplinks that are located near LMDS hubs, the LMDS service provider can balance the downlink and return link availability. This does not increase the complexity of the protocol, but only affects the order of the frequencies on the ordered frequency list.

The size of the interference zone around a hub receiver can be reduced by modifying the LMDS return link system design. Possible modifications include the use of a higher transmitter power at the subscriber unit, and the use of multiple directional hub receiver antennas. The use of a directional hub antenna would increase the availability for some users, but would not improve the performance in locations where both the LMDS subscriber and the co-frequency active FSS uplink are located in the main beam of the hub receiver antenna unless the increased link margin provided by the directional antenna increased the carrier power enough to overcome the effect of the interference. Multiple hub sector receive antennas would also increase the return link capacity, allowing operation on a frequency different from the interfering FSS uplink.

4.3 LMDS System Availability With FSS/LMDS Spectrum Protocol

Calculations of LMDS system availability were performed in Chapter 3 for a ubiquitous deployment of FSS uplinks and LMDS receivers without any exchange of system information. This section presents the results of the calculations of LMDS system availability with FSS uplinks operating with the FSS/LMDS Spectrum Protocol described in Section 4.2. Availability is calculated as the availability of the entire frequency band shared between the FSS and LMDS systems outside of a single reduced availability channel in each LMDS cell for the two LMDS systems studied here.

Figure 4-5 shows the performance of the CellularVision and Texas Instruments LMDS systems in the presence of 15 randomly located simultaneously active T1 rate TST uplinks with and without the spectrum protocol. Notice that for a required C/(N+I) of 13 dB, the LMDS system availability is increased to 99.96% for the FM video system and 99.97% for the digital data system. At a required C/(N+I) of 8 dB for the CellularVision system, the availability is increased to 99.98%. These availabilities were computed with all of the conservative assumptions described in Section 3.5. Real-world availabilities can be expected to be even higher. The Texas Instruments system shows slightly greater availability improvement due to the assumption that the first two uplinks in an LMDS cell

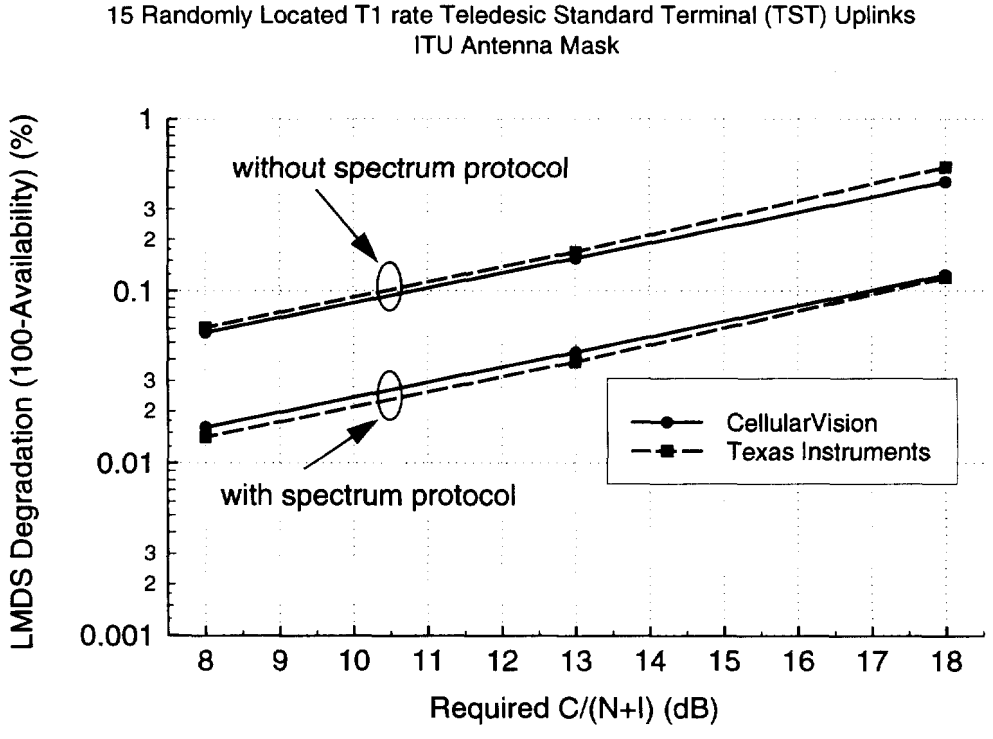
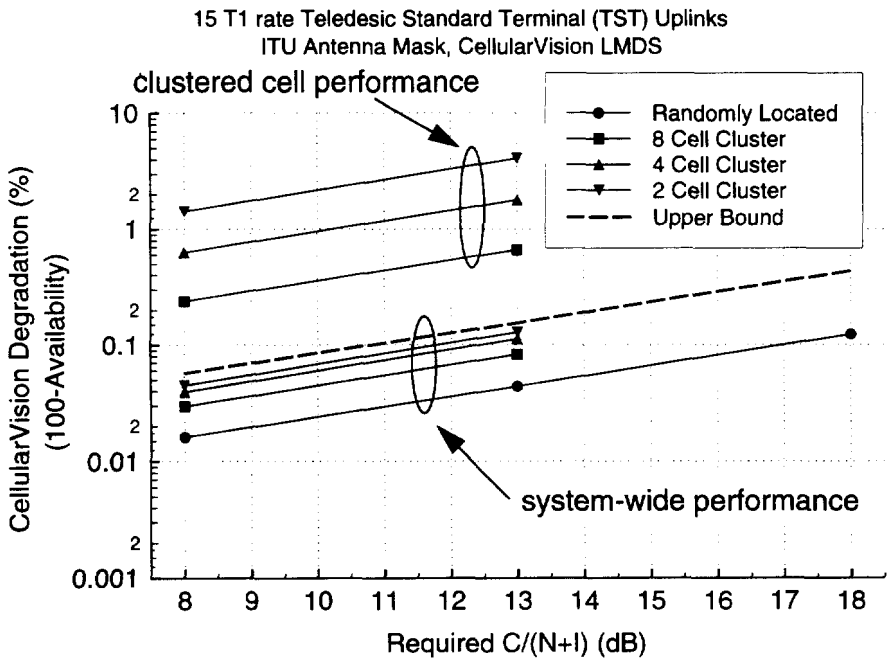


Figure 4-5. Improvement in availability (reduction in degradation) of LMDS hub-to-subscriber link with implementation of the FSS/LMDS spectrum protocol with 15 randomly located T1 rate TST uplinks.

do not cause harmful interference, whereas only the first uplink in an LMDS cell does not cause harmful interference to the CellularVision system. The slight performance difference at a given C/(N+I) is independent of modulation type. The modulation type determines the threshold value of C/(N+I) used to measure system availability. This performance improvement is somewhat offset by the amount of bandwidth (52 MHz vs. 18 MHz) where the availability is less than 99.9%. The availability of the reduced availability channel is slightly higher than the availability computed without the protocol in Chapter 3.

Figure 4-5 shows the LMDS performance with randomly located FSS uplinks. It was shown earlier (Figure 3-4 and Figure 3-5) that FSS uplinks clustered in a small geographic area can cause a higher percentage of signal degradation in the small number of LMDS cells where those uplinks are located. Figure 4-6 shows the performance of the CellularVision (top) and Texas Instruments (bottom) systems in the presence of clustered T1 rate TST uplinks operating with the spectrum protocol. This figure shows that the LMDS availability decreases when FSS uplinks are clustered in a small number of LMDS cells, even when the spectrum protocol is implemented. This occurs because only the first one or two uplinks in a cell can operate on frequencies such that they do not cause harmful interference in other channels. When uplinks are clustered, a greater number of these uplinks must operate on frequencies other than the ones corresponding to the reduced availability LMDS channel, causing harmful interference to surrounding LMDS receivers. The availability performance of the LMDS system in the presence of FSS uplinks operating with the protocol is upper bounded by the availability computed for randomly located T1 rate TST uplinks operating without the spectrum protocol. The amount of performance improvement provided by the FSS/LMDS Spectrum Protocol is directly dependent upon the size of the geographic region over which simultaneously active FSS uplinks are clustered. Although the availability in the cells where the uplinks are clustered drops below 99.9%, the "clustering factor" of simultaneously active uplinks will be constantly changing as links to the satellite are established and terminated. The calculations assume that 15 simultaneously active uplinks are *always* clustered in those few cells. Under actual traffic conditions, there will often be less than the maximum of 15 simultaneously active uplink terminals. Also, uplinks in LMDS cells other than where clustering is highest will access the FSS network reducing the average traffic in the clustered cells. The actual LMDS availability will be greater than the calculated availability, even in the cells where FSS uplink traffic is densely clustered. In addition, this does not include the effect of any of the conservative assumptions. Availability of 99.9% at a C/(N+I) of 13 dB can be further guaranteed by improving FSS uplink sidelobe levels by just a few dB as can be seen in Figure 4-7.



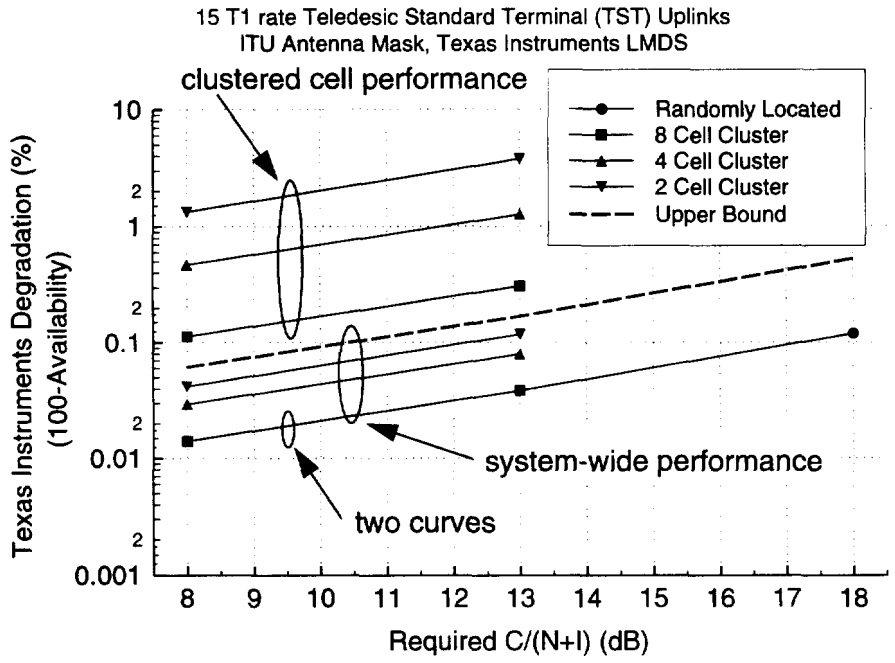


Figure 4-6. LMDS system performance for both the CellularVision (top) and Texas Instruments (bottom) hub-to-subscriber links with the spectrum protocol when 15 simultaneous T1 rate TST uplink transmissions are clustered in a small number of LMDS cells for the ITU antenna pattern mask.

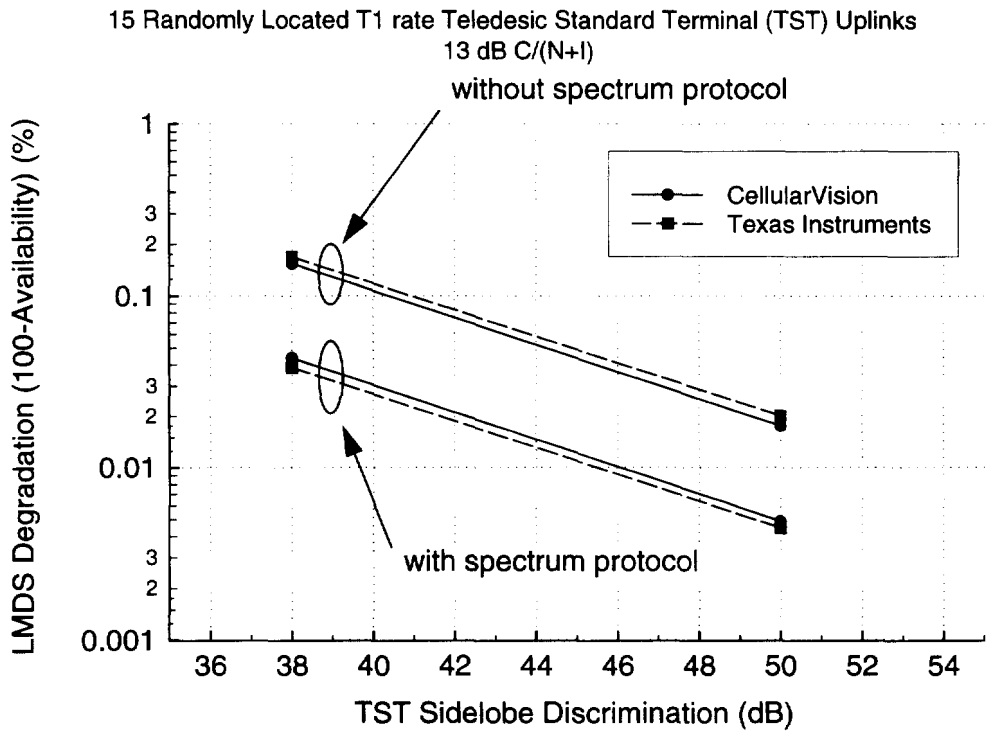


Figure 4-7. Improvement of LMDS availability with the FSS/LMDS Spectrum Protocol as a function of TST sidelobe discrimination when 15 randomly located T1 rate TST uplinks are simultaneously active.

With 1440 simultaneously active TSTs at 16 kbps, the spectrum protocol improves LMDS system performance as shown in Figure 4-8. For the CellularVision system, 133 TST uplink frequency slots are available in each set of frequency interleaved cells, and an additional 57 uplink frequency slots are available in each of 20 cell groups before any harmful interference is caused into subscriber receivers. For the Texas Instruments system, 189 TST frequency slots are available in each of 8 cell groups before harmful interference is caused. For a uniformly random distribution of FSS uplink locations, the spectrum protocol significantly improves performance from 99.65% to 99.996% at a 13 dB required C/(N+I) threshold. The CellularVision system availability at 8 dB C/(N+I) was 99.9% without the spectrum protocol. The improvement with the protocol was computed with the interference spectral density equal to the aggregate power of all interferers on the same LMDS channel, and represents conservative assumptions. The spectrum protocol improves the performance of the Texas Instruments system from 99.7% to 99.995% (13 dB C/N+I) in the presence of 1440 simultaneous 16 kbps interferers. Clustering of 16 kbps users was not considered since significant clustering of these users is significantly less likely than for T1 rate users. The results show that implementation of the spectrum protocol provides LMDS availability well in excess of 99.9% in the presence of 16 kbps TST interference. The results also confirm that the limiting factor on LMDS availability for interference from

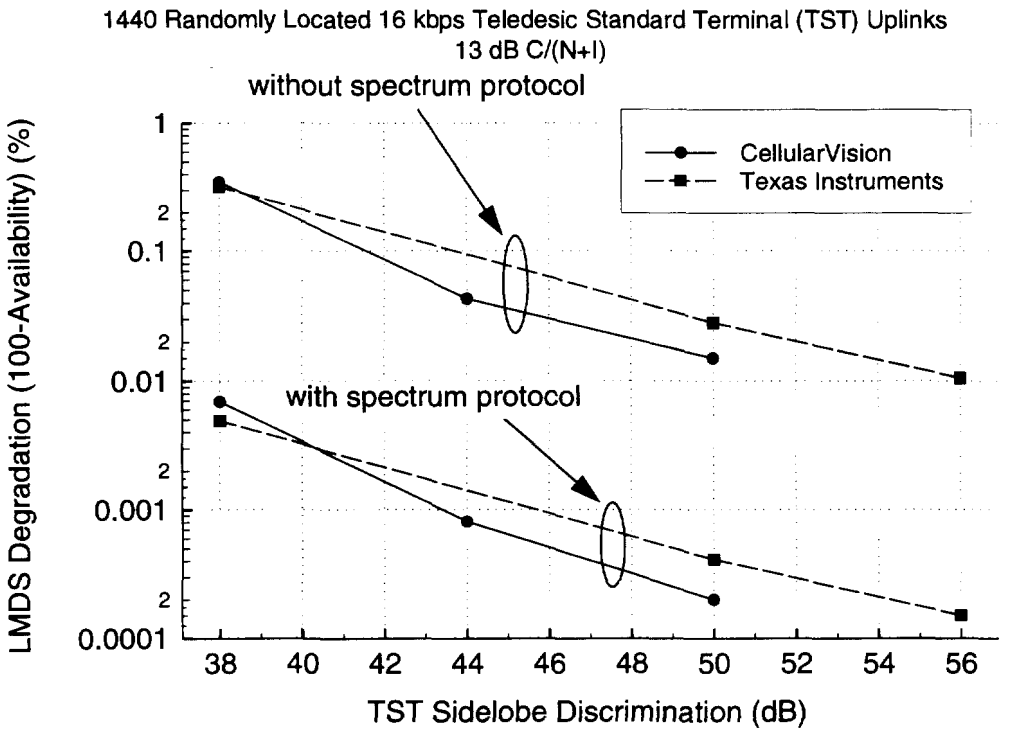


Figure 4-8. LMDS performance improvement for the CellularVision and Texas Instruments hub-to-subscriber links in the presence of 1440 simultaneously active 16 kbps TST uplinks.

Teledesic Standard Terminals occurs when the TSTs operate at the T1 data rate (1.544 Mbps) when the protocol is implemented.

The LMDS availability for T1 rate TST interferers was calculated based on the degradation in a single cell in the presence of active FSS uplinks. However, it may be possible for an FSS uplink to cause interference in adjacent LMDS cells due to cell overreach of the potential interference zone around each LMDS receiver; electromagnetic signals do not stop propagating at cell boundaries. To insure that this does not lead to a significant decrease in LMDS availability, multiple Monte Carlo simulations of 15 simultaneously active T1 rate TSTs operating with and without the spectrum protocol in the same area as a 64 cell CellularVision LMDS deployment were performed. If cell overreach were a significant problem, the simulated availability would be much less than the availability computed with the single-cell method described in Section 3.3.

Figure 4-9 shows the single-cell computed availability and the availability computed as the average of multiple Monte Carlo simulations for a required C/(N+I) of 13 dB. It can be seen that the simulated multi-cell availability is actually somewhat greater than computed via the single-cell method both with and without the spectrum protocol, indicating that cell overreach does not significantly affect LMDS availability. Cell overreach has potential a greater impact when the protocol is implemented because when an FSS uplink interferes

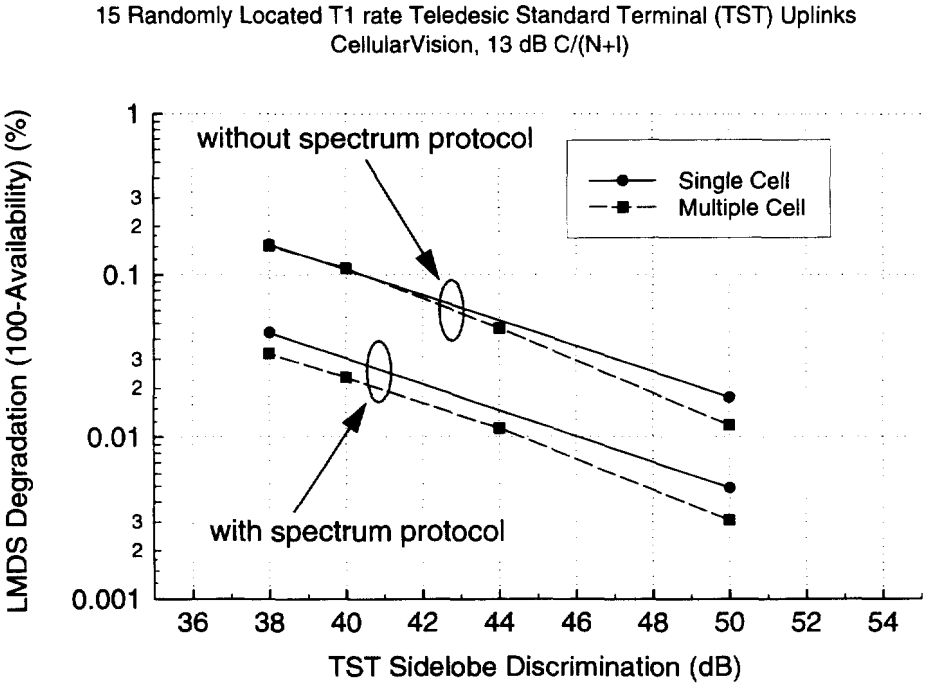


Figure 4-9. LMDS availability as computed with the method described in Section 3.3, and as determined via multiple Monte Carlo simulations.

with an LMDS receiver in an adjacent cell, the uplink is not operating on a frequency at the start of the ordered frequency list for the adjacent cell. The amount of cell overreach is directly proportional to the FSS uplink antenna sidelobe discrimination. The impact of cell overreach on the Texas Instruments system with T1 rate TST interferers is comparable to that for the CellularVision system. The results for 1440 16 kbps interferers already includes the possibility of cell overreach, including the effect of frequency interleaving in adjacent rows of cells and a different ordered frequency list in each cell.

4.4 Operational Aspects of the Spectrum Protocol

Implementation of the FSS/LMDS Spectrum Protocol will require communication between LMDS service providers and FSS service providers. Minor system design modifications will be required to implement the protocol. Each FSS uplink will have an ordered list of the frequencies to be used for transmission, obtained from the LMDS service provider. Upon initiation of a call, the uplink will need to traverse this list until an unused frequency is found. The list can be located in either each FSS Earth terminal, or in the satellite system database. The appropriate location depends upon the channel access procedure specified in the satellite system design. If located in the Earth station, the list could easily be loaded into memory once the fixed operational location of the terminal was known. For a satellite controlled access procedure, once the station ID of the uplink requesting service is known, the satellite can perform a database lookup to determine the appropriate frequency list to be used in finding the most appropriate operating frequency. This is no more burdensome

to FSS system operation than authentication of users accessing the system to insure that a user requesting access is a customer in good standing for customer billing purposes. For simplicity, there may be a limited number of possible channel ordering plans that would reduce the amount of additional traffic load caused by database access. Alternatively, channel list information could be updated periodically in the Earth station memory by information on the satellite's downlink transmissions. This method would also allow for changes in the LMDS frequency plan to be conveyed to the satellite earth terminals.

Determination of the appropriate channel list for an individual FSS Earth station should be determined by the potentially affected LMDS service provider in the geographic area where the uplink is located. One possible method for exchanging this information would be for the FSS service provider to supply the latitude and longitude of each Earth station to the LMDS service provider (or an industry-wide LMDS database maintenance organization). The potentially affected LMDS service provider will then supply the appropriate ordered frequency list for that Earth station where the frequencies on the list correspond to the operating frequencies of the satellite system. Once this information is entered into the satellite database (either in each Earth station, or a centralized database), the uplink will be authorized to transmit under the rules of the protocol. Verification of compliance with the protocol can easily be accomplished with the appropriate system diagnostic tools.

This proposed FSS/LMDS Spectrum Protocol does not appear to place an onerous burden on either FSS or LMDS system operators. In fact, Teledesic has stated, "the Teledesic Network as well as the SPACEWAY system allocate channels dynamically every frame based on the traffic demand" [2]. A simple modification to the channel access and dynamic reassignment procedure for FSS uplinks to insure compliance with the protocol should be straightforward to implement with minimal, if any, cost impact. The dynamic reassignment of channels should actually improve LMDS availability by shifting the operating frequency of an individual uplink to a different frequency that is closer to the beginning of the ordered frequency list once that frequency becomes available. Implementation of the protocol is a small price to pay to preserve global allocation of the 28 GHz band for satellite uplinks while allowing immediate economic deployment of LMDS.

Use of the spectrum protocol provides many benefits for both FSS and LMDS system providers by achieving co-frequency sharing in the 28 GHz band. In addition there are several minor FSS and LMDS system design changes that must be accommodated. The burden of achieving co-frequency sharing appears to be evenly divided between FSS and LMDS. LMDS will operate with reduced (less than 100%) availability, and will occasionally operate with reduced signal quality. Providers of both services must communicate with each other to implement the protocol. FSS systems will have to implement the protocol in the channel access and dynamic reallocation procedures. Table 4-1 summarizes the benefits and challenges of the FSS/LMDS Spectrum Protocol for both LMDS and FSS systems.