A PROPOSED METHOD FOR QUANTIFYING UPSTREAM INGRESSING CARRIERS

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Abstract

The authors propose a methodology for analyzing ingressing carriers and intermodulation products independently from electrical transient interference. The evaluation results are presented in a simple form which can be used to rate system performance, judge the effects of mitigation measures, and predict changes resulting from changes in operating parameters.

INTRODUCTION

Upstream (subscriber-to-headend) transmission in broadband distribution systems differs materially from that in the downstream direction due, in part, to the frequency ranges chosen for reverse transmission and the branching nature of the network.

The reverse spectrum includes frequencies used by many over-air transmitters, including citizens band, amateur radio operators and short wave broadcasters. Also, second-order intermodulation (IM) products from mixing among downstream signals are strongest at the upstream frequencies. Finally, electrical transients (from a multitude of sources) have a spectral content which is stronger at frequencies below 30 MHz.

Network branching and the lack of switching cause signals introduced at all points in the system to combine at the optical node or headend, increasing the chances of interference.

PREVIOUS STUDIES

Several authors have reported the results of studies of ingress, including extensive work done by Rogers Cable Television and CableLabs.[1] The results of such studies have frequently used detailed tabular and/or graphical information on ingressing signal levels and frequencies over various time periods.

This information has been invaluable in gaining a general understanding of the challenges associated with upstream data transmission. Unfortunately, the typical complex presentation of the data is hard to relate to network performance and many of the studies involved complex analyses of the raw data and/or special instrumentation.

REQUIRED SEPARATION OF TRANSIENTS AND CARRIERS

One difficulty has been that much data has been taken with spectrum analyzers so that "events" included the effects of both short electrical transients and longer term ingressing radio carriers and distortion products.

Since the duration of electrical transients was typically short compared with the sweep rate of the analyzer, they appeared as narrow-band interfering signals at whatever frequency the analyzer happened to be receiving at the time of occurrence, whereas the spectrum of most transients includes the entire return band.

In addition to the problems of accurately quantifying the impact of transients in such mixed presentations, they need to be measured and treated separately because the tools for dealing with these impairments are very different. Discrete frequency problems can be avoided by moving upstream transmitter frequencies, while short broadband transients can best be avoided through error correction and/or interleaving techniques, combined with re-transmission when required.

SOLUTION REQUIREMENTS

A useful tool for evaluating discrete product interference should have the following characteristics:

1) It should have good statistical processes which will average out the quasi-random nature of ingressing signals, so that general ingress conditions in a plant can be determined consistently enough that the effect of, for instance, various mitigation measures can be measured.

2) It should provide sufficient data to enable users to choose channel frequencies and/or frequency ranges and to predict the ingress-related performance that will result.

3) It should allow the user to evaluate the service availability effects of changing such parameters as data channel level or frequencies.

4) Given that many transmitters are frequency agile, it should be able to predict the availability gain resulting from various degrees of mobility.

5) Perhaps most importantly, it should provide a limited number of "figures of merit" which can be used to judge the overall ingress situation without further analysis.

The proposed methodology meets all these criteria.

OVERALL PROJECT

This tool was developed as part of an extended and detailed study of data transmission through HFC cable systems. Previous reports have included a general status report on the study,[2] as well as a detailed study of downstream laser clipping.[3]

Overall goals of the study have included the providing of guidance to product designers on the quality of the transmission path and the development of field engineering tools and methods for evaluating cable systems' ability to carry bi-directional digitally-modulated signals. The development of simple methodologies for quantifying all types of ingress has been a major challenge.

AVOIDING ELECTRICAL TRANSIENTS

As with other researchers, we used a spectrum analyzer as our basic instrument for gathering ingress data. The analyzer was programmed to make measurements over a period of time which were then downloaded to a standard personal computer for analysis.

In order to understand how to collect information on ingressing carriers that was not "polluted" by electrical transients, we first evaluated transient events as they appeared at the headend. Although methods for evaluating transient ingress are not discussed in this paper, an understanding of their general nature is important.

The waveforms of representative transients were recorded using a fast digital storage oscilloscope directly attached to the upstream optical receiver in the headend. Using the instrument's internal fast Fourier transform (FFT) capabilities, both the time and frequency domain data were saved for analysis. Figures 1-4 show the general range of observed events. The upper trace in each picture is the time signature of the waveform, while the lower trace is the same event plotted in the frequency domain.

As can be seen, most transients take the form of "bursts" lasting no more than a few microseconds. By contrast, ingressing radio signals are present for much longer time periods. We therefore "filtered" out transients by reducing the spectrum analyzer's video bandwidth to only 300 Hz. Thus the rise time of the video circuitry was about 1.2

milliseconds - many times the typical transient duration. By slowing down the sweep rate so that the dwell time per frequency was sufficiently long, accurate recording of discrete carrier levels was still preserved.

DATA GATHERING

The spectrum analyzer was connected to the headend optical receiver output. The node analyzed passes approximately 2,000 homes, with a forward cascade of four amplifiers, and contains between 40 and 50 active devices. The reverse passband extends from 5 to 30 MHz. The only intentional upstream signal present was a bursted QPSK test signal centered at 24 MHz.

Approximately 1300 basic customers are served by the system, which is fully two-way to every tap. No filters or drop equalization are used, so the node is "wide open" to ingress.

The analyzer was set up to record peak and "average" (see below) signal levels at frequency intervals of 100 kHz and over time windows of one hour. While this limited the number of data points to be analyzed, shorter time periods would result in a more useful analysis and we expect to do a more detailed time-axis analysis in the future.

The resolution bandwidth was set to 300 kHz and the video bandwidth, as discussed above, to 300 Hz. With these settings, the sweep rate was less than one per second, but still fast enough to get a statistically valid number of samples in each hour.

At the end of each measurement time period the data was downloaded to the connected microcomputer, so that two matrices were created, each with time on the horizontal axis and frequency on the vertical axis and with the peak levels in the cells of one matrix and the "average" levels in the other.

DATA ANALYSIS

Figure 5 shows the "raw" data from the peak value chart. This is not unlike those published by several other researchers. The modem signal at 24 MHz is easily seen as are the highly variable peaks associated with CB radios in the 27 MHz region. This system is remarkably free from common path intermodulation distortion products which would have shown up at 6 MHz and its harmonics. Finally, it shows the typical rise in overall ingress levels at lower frequencies. The chart is relatively free of the random spikes caused by transients, while data taken with wider video bandwidths was dominated by large amplitude spikes.

Determining Threshold Interference Levels

Since the aim of the tool was not just to collect level information, but to relate that information to service disruption potential, the next step was to carefully measure the maximum level of interfering carriers that would not disrupt the QPSK-modulated signals under consideration. This was measured under both noise-free conditions and with a carrier-to-4 MHz noise ratio of 29 dB. The results were consistent within about 1 dB. As shown in Figure 6, the receiver was essentially immune to signals offset by more than 900 kHz from the channel center, but a carrier-to-interference (C/I) ratio of approximately 14 dB was required for signals closer to the channel center to maintain a BER below 10^{-5} (our arbitrarily defined failure level). Tests also showed that the BER changed by a little over one order of magnitude for each decibel change of interfering signal level.

Given the required C/I ratio and the desired signal level, we next computed the threshold interference level. Clearly, for any frequency, if the peak level did not exceed the threshold during a given measurement period, the data could be ignored.

In cases were the peak value of a signal exceeded the threshold, we attempted to approximate the percentage of time the carrier was present. In our early analyses, we have used a peculiarity of the particular analyzer model which is that its "average" power reading is actually an average of the screen positions on successive sweeps, rather than true average power. While this is a problem for some measurements, we used it to advantage. In particular, if the carrier level, when present, is relatively constant (within 10 dB or so) the fractional time present can be approximated using:

$$\frac{\textit{On Time}}{\textit{Total Time}} \simeq \frac{(\textit{Peak}-\textit{Noise})}{(''\textit{Average}''-\textit{Noise})}$$

where: Peak is the maximum recorded power level, using the analyzer's peak detector function, at a particular frequency and over all the sweeps during a time interval;
Noise is the observed system noise floor at the resolution bandwidth used; and
"Average" is the average of the screen positions on successive sweeps.

This will be a much better approximation when time intervals are relatively short. Alternately, at the expense of more post-processing, we could save the data from each sweep separately.

Frequency Unavailability

Using the above method, we can create a chart showing what percentage of time each frequency is impaired. Figure 7 shows this transformation of the raw data.

Note that, although the peak levels in the 27 MHz region were very high, since any individual carrier is generally present a relatively small fraction of the time, the percentage unavailability is low compared with the weaker, but longer duration, signals at the lower end of the spectrum. Also, note that the 24 MHz modem signal is present, but at a level which reflects the light duty cycle of the test sequence running at that time.

Channel Unavailability

Although the frequency unavailability chart is certainly more readable than the raw signal levels, it is still not useful in predicting system performance. To do that, we need to examine each possible communications channel over its susceptibility bandwidth. As discussed above, we found 2 MHz QPSK channels to have a "susceptibility bandwidth" of about 1.8 MHz. Thus, an ingressing signal will affect any channel whose center frequency is within ±900 kHz.

Figure 8 reflects this by determining the unavailability of communications channels as a function of channel center frequency and time. As can be seen, rather broad sections of spectrum can be affected by combinations of closely-spaced ingressing signals. For instance, if the 27 MHz CB interference is to be avoided, the only channel frequencies available between the 24 MHz test signal and the top of the spectrum are at 26 and 29 MHz.

The spreadsheet, in addition to the chart, includes a table of average channel availability as a function of center frequency, so that users can match channel quality to service requirements.

Service Unavailability

Although the above chart shows the data for fixed channels, many proposed upstream services employ frequency agile transmitters and include logic to direct communications to clear channels within a specified service bandwidth.

In order to estimate the possible "availability gain" from such a system, we added a Service Bandwidth definition to the model. It then calculates the service unavailability in each time slot by choosing the least impaired channel frequency. The gain relative to any fixed channel can be significant. Figure 9 shows the minimum possible unavailability of a service extending from 9-14 MHz, as an example. Also plotted are the unavailability of the worst, best and average of all channel frequencies in the service range. As can be seen, even the best fixed channel has an unavailability exceeding 10% at some times, while the overall service availability is 100% except for one time slot for which unavailability rose to just over 10%.

Overall, the defined service unavailability was just 0.25%, compared with 5.3% average for all possible channel frequencies in the service group - a reduction factor of greater than 20.

It should be stressed that this improvement factor is the theoretical maximum and assumes that:

A) the system responds instantaneously to interference conditions and,

B) that it correctly chooses the best new frequency for communications.

Nevertheless, it is a useful tool for judging the relative performance possible as a function of spectrum utilization.

Summary Data

While the graphical data presented in this paper is useful for understanding the analysis process, the system generates several overall quality values that may be more useful for system maintenance purposes:

A) The percentage unavailability of all frequencies, averaged over time and frequency.

B) The percentage unavailability of all possible channel center frequencies, averaged over time and frequency.

C) Given a defined spectrum for a particular service, the average unavailability of all possible channels within the service group.

D) The minimum theoretically possible unavailability for a service using agile transmitters.

These numbers can be used as a reference to compare systems, to judge overall quality trends within a system and to evaluate the results of ingress mitigation measures.

Parametric Analysis

Another use for the tool is to evaluate the effects of technical options. For instance, the level of the data carrier can be changed and the effect on unavailability seen immediately. Similarly, if an operator wished to evaluate whether the system were suitable for carrying more aggressive modulation schemes, such as 16 QAM, all that is required is to change the required C/I ratio. Finally, the quality of both fixed-frequency channels and variable service bandwidths for agile systems can be examined. With further work, the model may accommodate different channel bandwidths.

RELATIONSHIP OF INGRESS TO OVERALL PERFORMANCE

The overall BER of an upstream data channel is affected by broadband noise, transient electrical interference, the ingress effects and IM products discussed in this paper, and a host of other effects which fall primarily in the realm of failures or mis-adjustments. Our test results to date have indicated that, absent discrete carrier and/or IM in-channel interference, electrical transients are the primary cause of data errors. Often transients are of sufficient amplitude to cause the upstream laser to go into hard clipping. Depending on their duration, various forward error correction techniques may be useful as defensive measures.

By contrast, discrete carriers have no effect unless they fall in a channel and are of sufficient amplitude. In that case, however, the slope of error rate vs level is very steep, so that a discrete carrier is likely to either cause no problem or a total loss of communications. Given that these signals are present for relatively long time periods, their presence is more easily described in terms of availability than BER.

A somewhat surprising result of field tests is that even if an out-of-band ingressing carrier is of sufficient amplitude to cause fairly severe clipping, it has no effect on data integrity unless a harmonic of the interfering carrier should happen to fall in-channel with sufficient amplitude.

When it does occur, the only defense against a long-term interfering carrier is frequency agility. However, the dynamics of ingressing signals may be most useful to product designers in determining optimal algorithms for control of upstream transmitter frequencies.

SUMMARY

The methodology and model described offer a method of quantifying the performance of cable systems with respect to upstream discrete carrier ingress and common path IM products, independently of the effects of electrical transients. The authors feel that is essential because of the different nature of those forms of signal degradation and available countermeasures.

The procedure uses a standard spectrum analyzer, similar to those in common use in cable systems. The post-analysis of the recorded data is performed using a simple (if somewhat large) Excel® spreadsheet. The model allows users to judge the effects of various operating conditions, and can aid operators in choosing operating frequencies and allocating spectrum among services.

The authors expect to further refine the data gathering process in the near future, in order to strike an optimum balance between resolution and spreadsheet size.

ACKNOWLEDGMENTS

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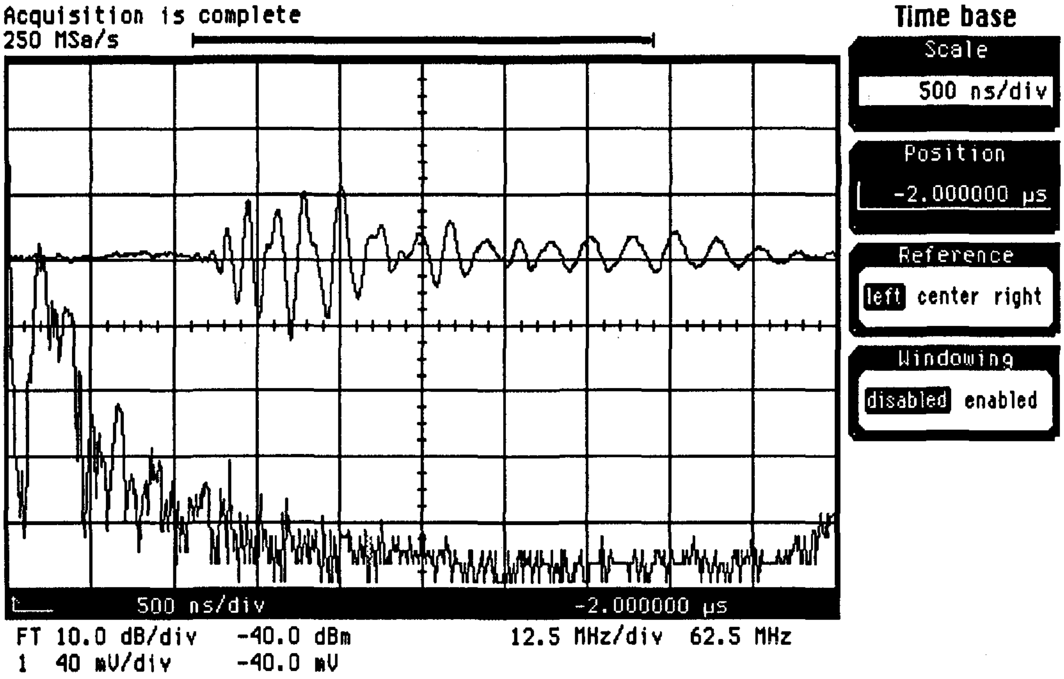
END NOTES

1.CableLabs, “Two-Way Cable Television System Characterization,” internal CableLabs document, 1995.

2.Rex Bullinger and Dave Large, “Status Report: Hewlett Packard Study of Bi-Directional Data Transmission Conditions in Cable Television Systems,” *HFC '96 Conference*, IEEE/SCTE, September, 1996.

3.Rex Bullinger and Dave Large, “Downstream Laser Clipping: Field Measurements and Operational Recommendations,” 1997 Conference on Emerging Technologies, SCTE, January 1997.

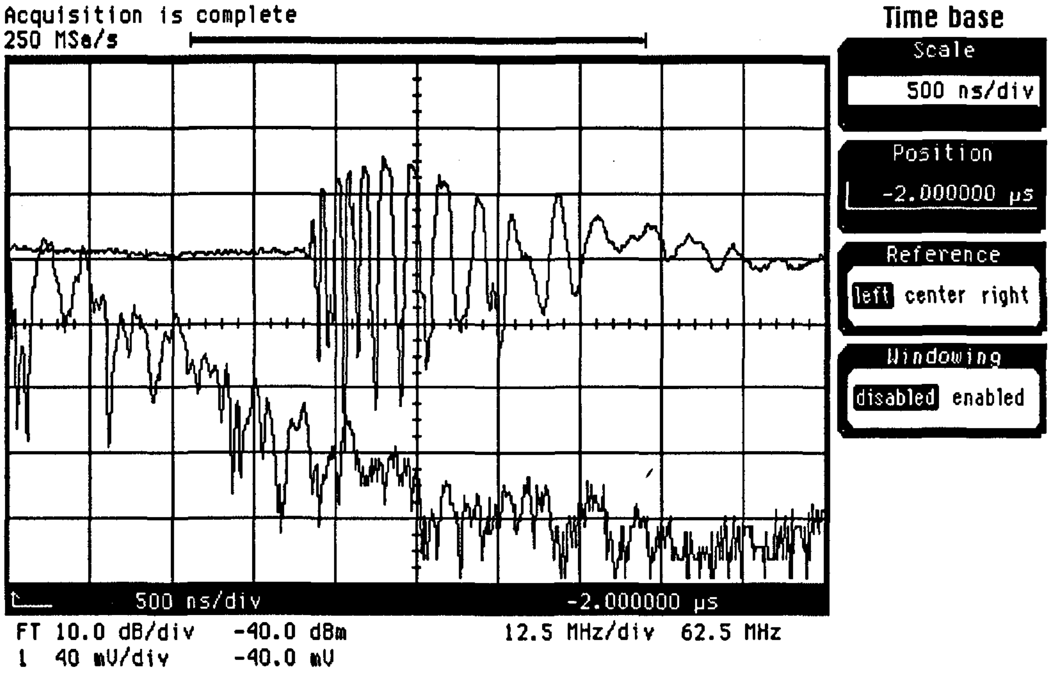

Acquisition is complete
250 MSa/s

500 ns/div -2.000000 µs

FT 10.0 dB/div -40.0 dBm 12.5 MHz/div 62.5 MHz
1 40 mV/div -40.0 mV

Time base
Scale 500 ns/div
Position -2.000000 µs
Reference ● left ○ center ○ right
Windowing ● disabled ○ enabled

Figure 1: Typical electrical transient and its Fourier transform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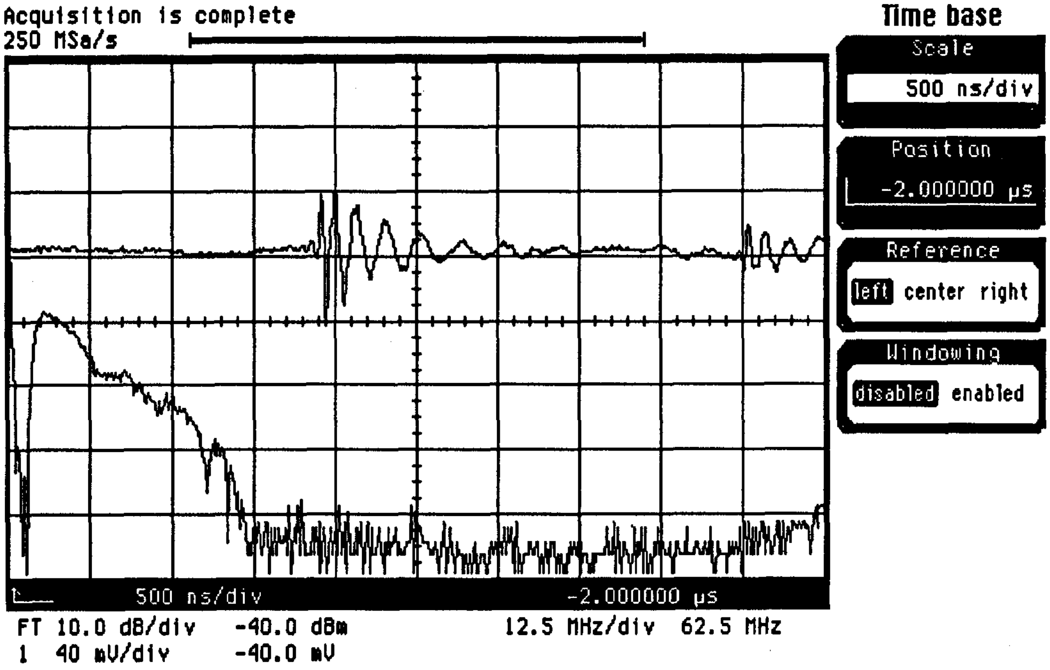
250 MSa/s

500 ns/div -2.000000 µs

FT 10.0 dB/div -40.0 dBm 12.5 MHz/div 62.5 MHz
1 40 mV/div -40.0 mV

Time base
Scale 500 ns/div
Position -2.000000 µs
Reference ● left ○ center ○ right
Windowing ● disabled ○ enabled

Figure 2: Large transient with clipping

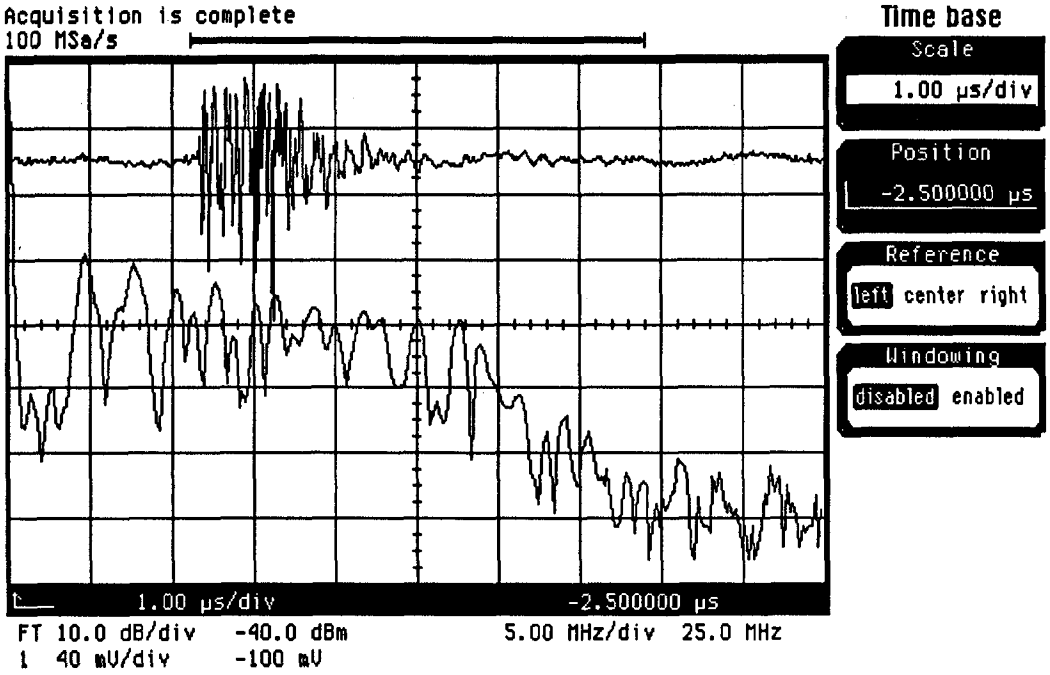


Acquisition is complete
250 MSa/s

Time base
Scale
500 ns/div
Position
-2.000000 µs
Reference
left center right
Windowing
disabled enabled

500 ns/div -2.000000 µs
FT 10.0 dB/div -40.0 dBm 12.5 MHz/div 62.5 MHz
1 40 mV/div -40.0 mV

Figure 3: Short transient with smooth frequency signature



Acquisition is complete
100 MSa/s

Time base
Scale
1.00 µs/div
Position
-2.500000 µs
Reference
left center right
Windowing
disabled enabled

1.00 µs/div -2.500000 µs
FT 10.0 dB/div -40.0 dBm 5.00 MHz/div 25.0 MHz
1 40 mV/div -100 mV

Figure 4: Transient with flat frequency signature

Figure 5: Peak Levels vs Frequency and Time

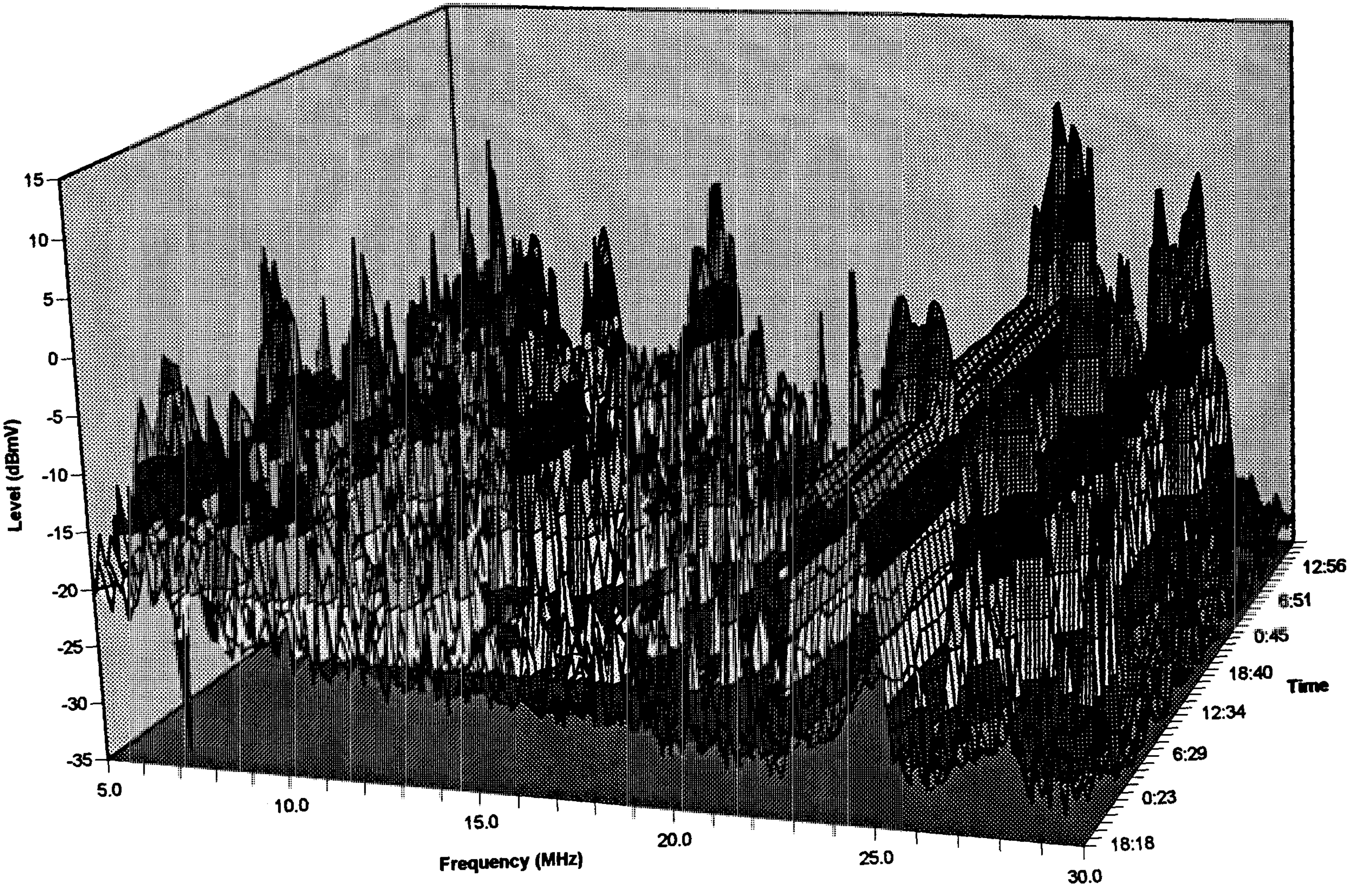


Figure 6: C/I Threshold for Discrete Interfering Carriers

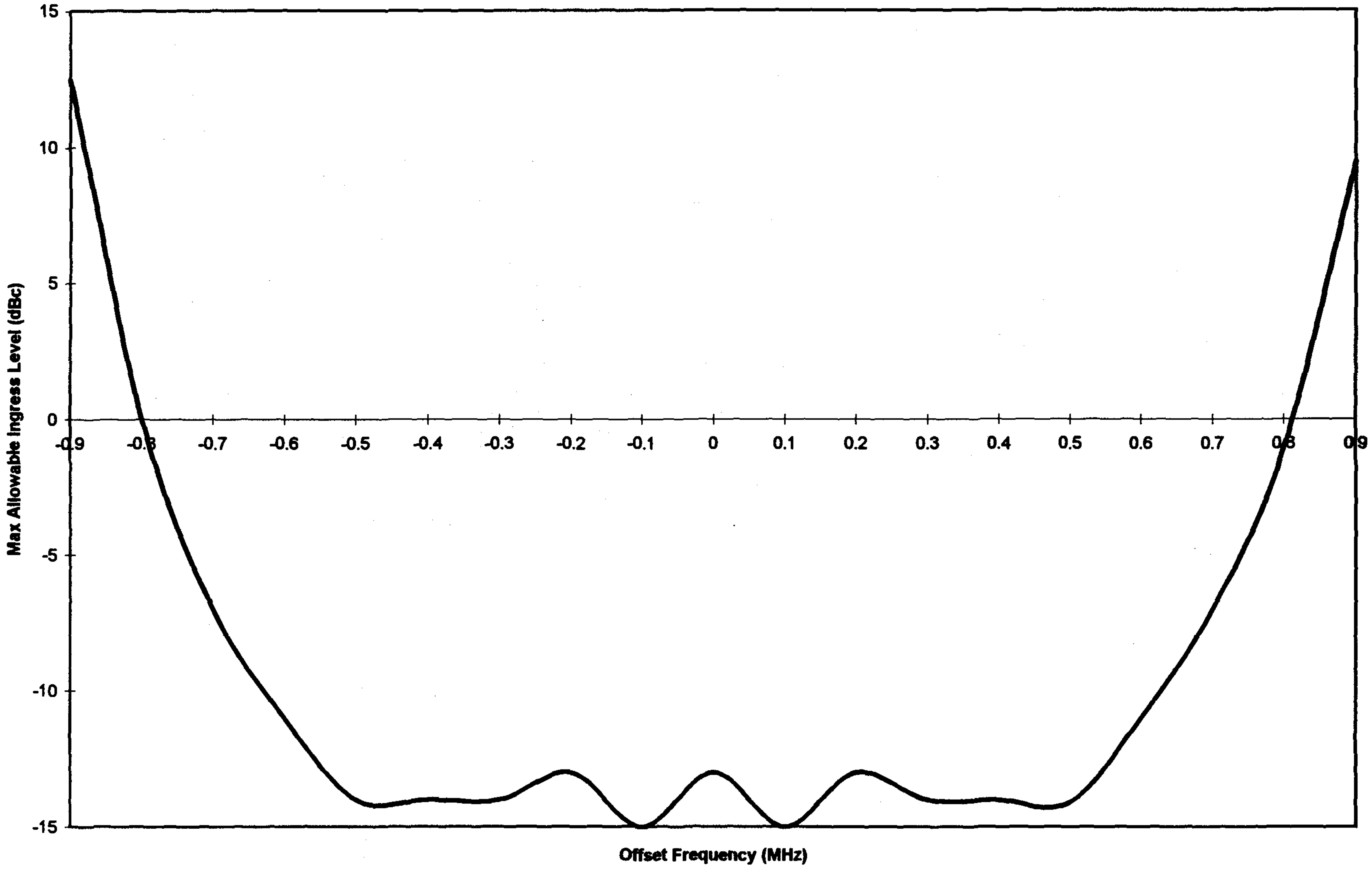


Figure 7: Frequency Unavailability vs Time

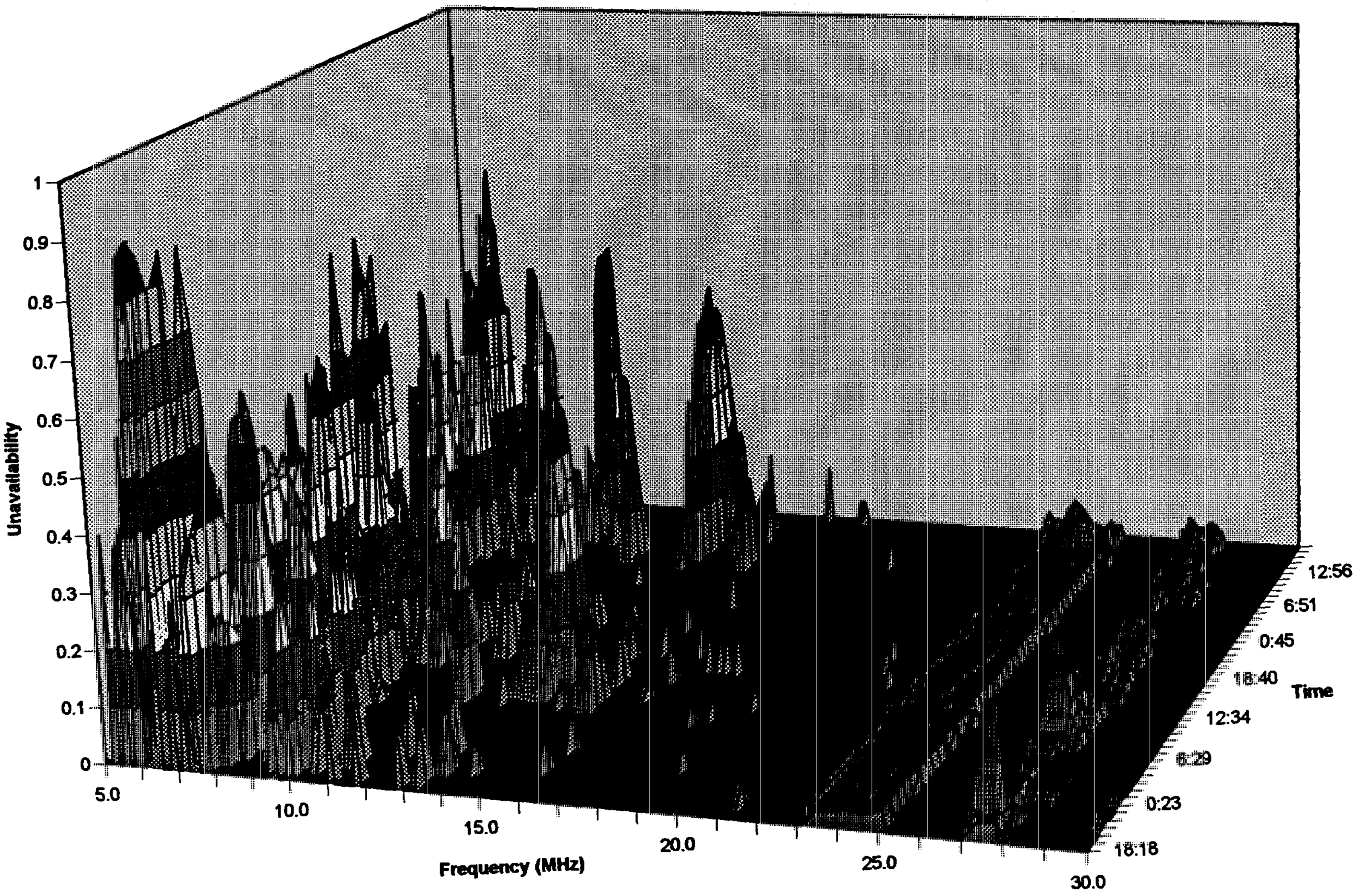


Figure 8: Channel Unavailability vs Frequency and Time

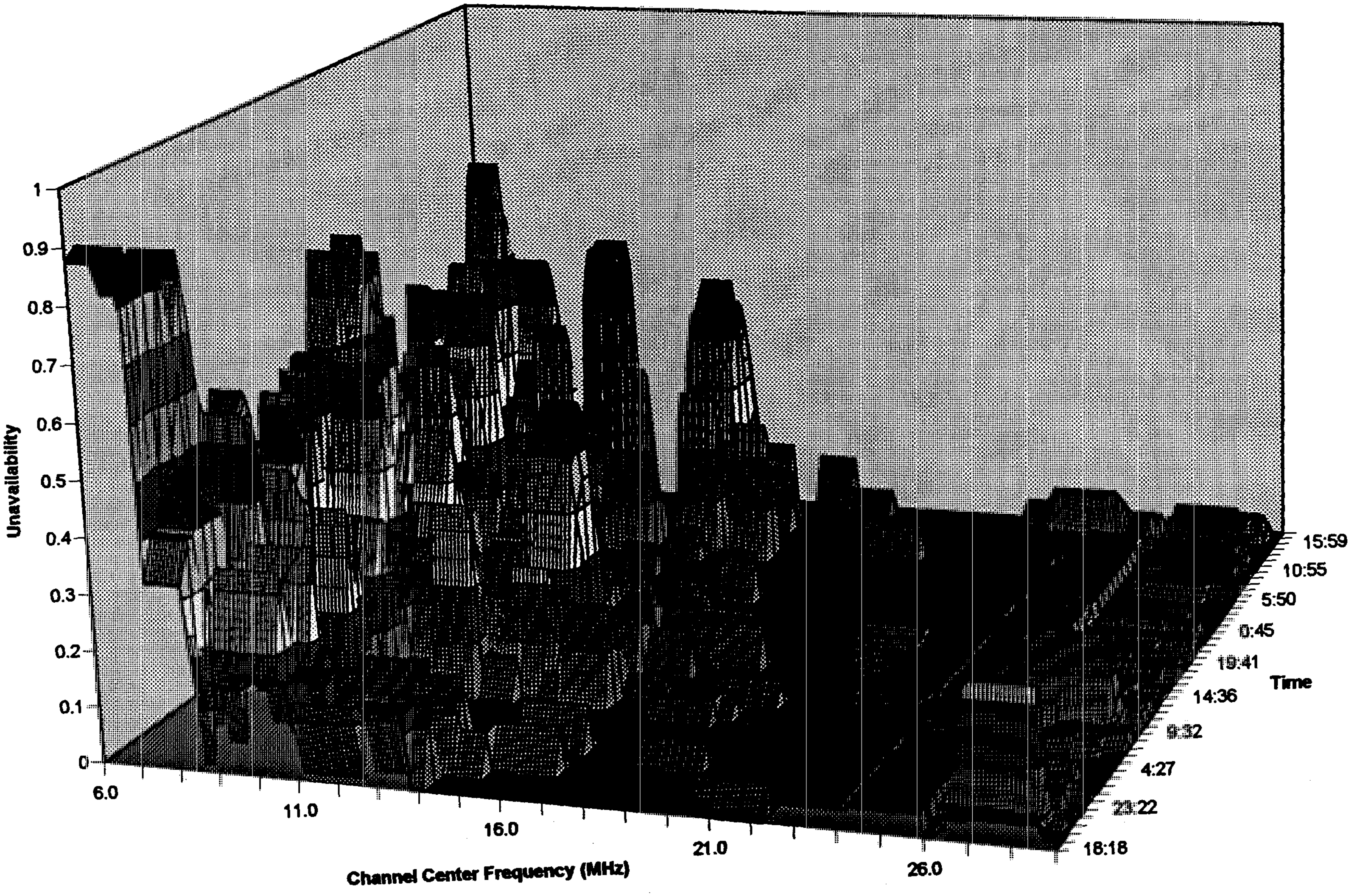


Figure 9: Unavailability of Service Group and its Channels vs Time

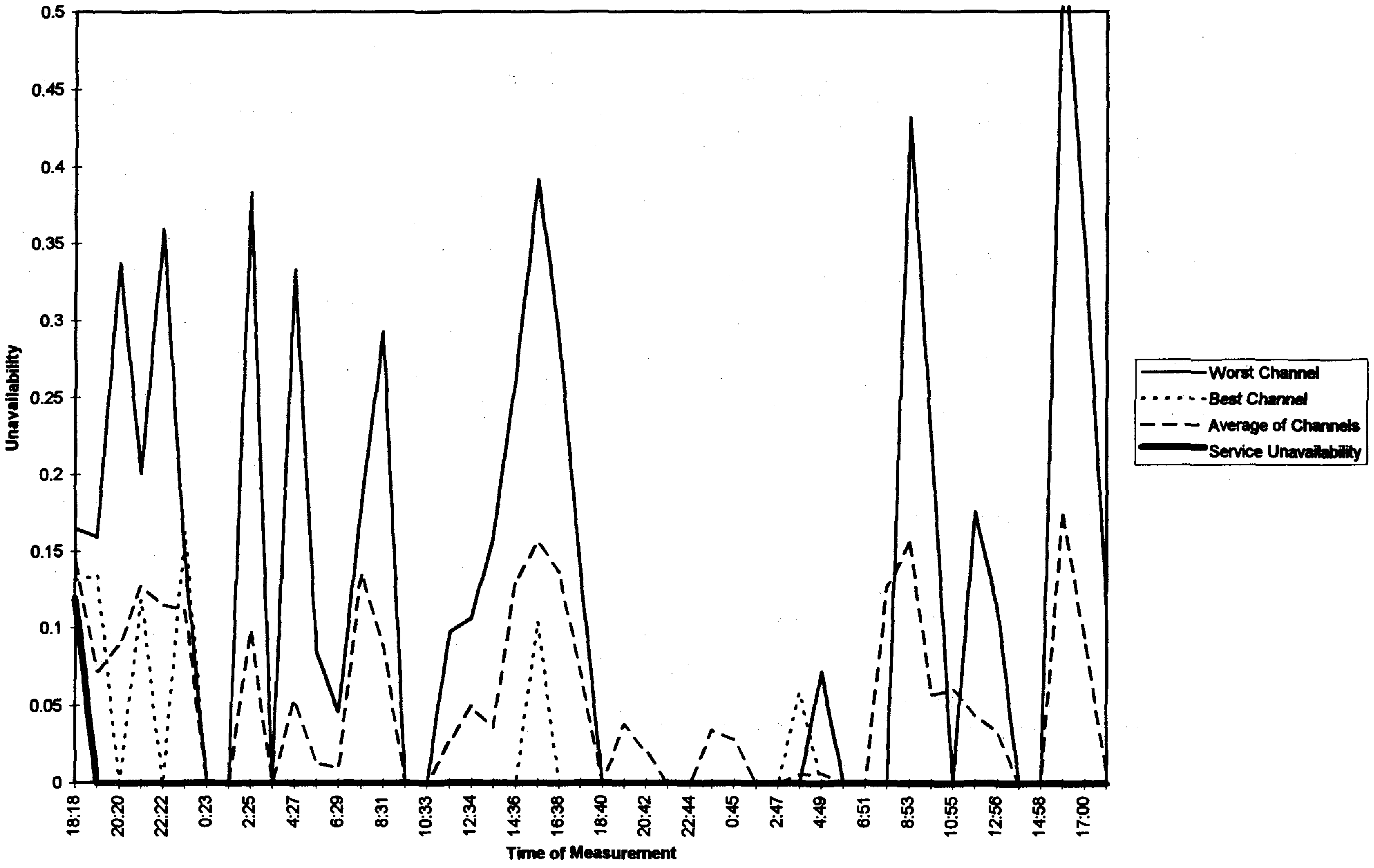


Figure 10: INGRESS EVALUATION CALCULATOR: USER INPUT AND SUMMARY RESULTS

Spectrum Analyzer Settings	
Start Frequency	2 MHz
Stop Frequency	42 MHz
Resolution Bandwidth	300 kHz
Video Bandwidth	300 Hz
Reference Level	30 dBmV
Scale Factor	10 dB/div
Measurement Period	60 Minutes
Measurements/sweep	401

Data Collection Parameters	
Start date	1/1/97
Start time	6:18:24pm
Collection period	48 hours
Location	Node 3
Noise Level at RBW	-35 dBmV
Notes	24 MHz modem signal (intermittantly)

Data Service Parameters	
Normal data carrier level	-2.3 dBmV
Required C/I ratio	14.0 dB
Data channel bandwidth	2.0 MHz
Service start frequency	9.0 MHz
Service stop frequency	14.0 MHz
Modem Tuning Resolution	125.0 kHz
Susceptibility Bandwidth	1.8 MHz
Return Spectrum Start Freq	5.0 MHz
Return Spectrum Stop Freq	30.0 MHz

Intermediate Calculated Parameters	
Interfering carrier threshold level	-16.3 dBmV
Minimum channel center frequency	10 MHz
Maximum channel center frequency	13 MHz
Number of usable channel frequencies	31
Equivalent screen position noise value	1500
Possible min channel center frequency	6 MHz
Possible max channel center frequency	29 MHz

Summary Results					
Average service unavailability	0.25%	Average service availability	0.997517	Avail. gain vs average svc chan	21.38265
Average unusable frequencies	2.33%	Average chan unavail (ttl)	6.83%	Average service chan unavail	5.31%