

This paper was written in 1999 by Doug Iles for the then ntl.

Since this paper was written, ntl has been purchased by Macquarie Communications Infrastructure Group (MCIG) and has been rebranded Broadcast Australia.

Doug continues to work at Broadcast Australia in the area of technical development. Since writing this paper Doug has been promoted to Media Systems Manager for the Broadcast Systems Team which is responsible for developing new and evolving technologies including Mobile TV, digital radio and infocasting.

Large Area Single Frequency Networks

A Field Study into the Practical Applications

Executive Summary

The ABA channel planning process has highlighted a shortage of available television broadcasting spectrum during the extensive simulcast period when commercial and national television programs will be transmitted in both analogue and digital format.

Single Frequency Networks (SFNs) allow a number of transmission sites to operate on the same frequency. They are spectrum efficient as they utilise less spectrum by requiring fewer frequency assignments. SFNs are being used successfully by ntl and other broadcasters in numerous overseas locations eg Spain, Portugal and Singapore, but only in situations where the distance between transmission sites is less than 38km.

ntl believes that SFN technology, if applied to the Australian situation, would have the potential to deliver improved spectrum efficiency, particularly in areas such as Sydney. In this particular case, spectrum congestion results in less than the target number of channels being made available to broadcasters and datacasters during the simulcast period. However, some of the proposed Sydney SFNs would need to operate over large areas ie up to distances of 70km to deliver improved spectrum efficiency.

In June 1999, after extensive modelling of SFN operations confirming the viability of large area SFNs, ntl established a SFN in the Canberra region and trialled its operation. The purpose of the trial was to test whether a real life large area SFN functioned in accordance with the theoretical study.

The ntl trial conformed to the proposed technical guidelines for DTTB transmissions as set out in the ABA Planning Guidelines. The two test sites chosen were Black Mountain Tower, Canberra and Bowning Hill, 60km from Canberra.

The trials were conducted over a two month period and supported ntl modelling predictions of the viability of large area SFNs. However, as expected, and consistent with the development of all digital broadcasting and transmission equipment, the trials underlined the importance of setting standards, particularly for the receiver industry. It will be important that both the digital television and datacasting industries work with receiver manufacturers to ensure the development of receivers which have been appropriately designed to receive signals transmitted via SFNs.

While the development of large area SFNs will be important for Australia it will also be of significant interest to other countries that are experiencing spectrum shortages.

Abstract

One of the major proposed advantages of the DVB-T transmission system adopted for use in Australia is the concept of the Single Frequency Network (SFN). A SFN aims to employ a number of transmission sites operating on the same frequency without causing interference. This has the potential to increase coverage whilst minimising extra spectrum requirements.

So far, DVB-T SFN networks have been developed and trialled overseas using fairly small transmission site separations, and using UHF spectrum particularly. It has been suggested that, for Australia, SFNs over very large distances (up to 70km) might be possible, and particularly desirable, for use in heavily-congested metropolitan areas.

Consequently ntl, in association with the Australian Broadcasting Authority (ABA), conducted a two-site SFN trial to examine practical issues involved with the setting up of such a large area SFN. Such issues included:

- Distribution of program to sites.
- Synchronisation of program within the SFN.
- Setting up of transmission site delays in the SFN.
- Performance of practical receivers in such a SFN.
- Ability to successfully model and plan such a SFN.

This paper presents a summary of the trial and some conclusions from examining the feasibility of the use of such networks.

Presenter Profile

Doug Iles works for ntl in Canberra as a member of a team involved in planning terrestrial broadcasting networks. Doug previously worked in the National Transmission Agency (NTA) where he set up the first Australian demonstration of DVB-T at UHF involving adjacent channel combining.

The rest of Doug's career has been spent in planning broadcasting services in the Dept of Transport and Communications after completing a Bachelor of Engineering (Electrical) at the University of Western Australia in 1989. He was born in Fremantle, WA.

Introduction

The need for an Australian SFN Trial

The SFN Concept

A DVB-T SFN is defined as one where each transmission's set of carriers must be transmitted:

- on the same frequency.
- at a particular exact time relative to each other; and
- using identical streams of data.

SFN performance is normally limited over distances corresponding to the 'guard interval' of the particular transmission mode being used. However, in certain situations SFNs might be possible, beyond the guard interval, ie over larger areas. This 'large area SFN' approach has been suggested for DTTB planning in certain markets in Australia.

Preliminary Work

Planning, Modelling and Testing

Transmission Mode

The ntl trial conformed to the proposed technical transmission guidelines for DTTB planning in Australia ie 64QAM constellation, 2/3 FEC rate, 1/8T guard interval and using the 8k carrier mode for a SFN. This guard interval corresponds to a time delay difference of 128us or the time taken for radio waves to travel approximately 38.4km.

Site Selection

As ntl has an existing DTTB trial facility at Black Mountain Tower (BMT), Canberra, it was chosen as the trial site for the main transmission. Bowning Hill, NW of Yass, was identified as the second trial site. Bowning Hill is 60km from BMT, over one-and-a-half times the guard interval, enjoys good quality receive signals from the main transmission at BMT and has an established communications infrastructure, making installation of equipment more practicable. The trial used VHF channel 12 transmissions from both sites.

Preliminary Reception Modelling

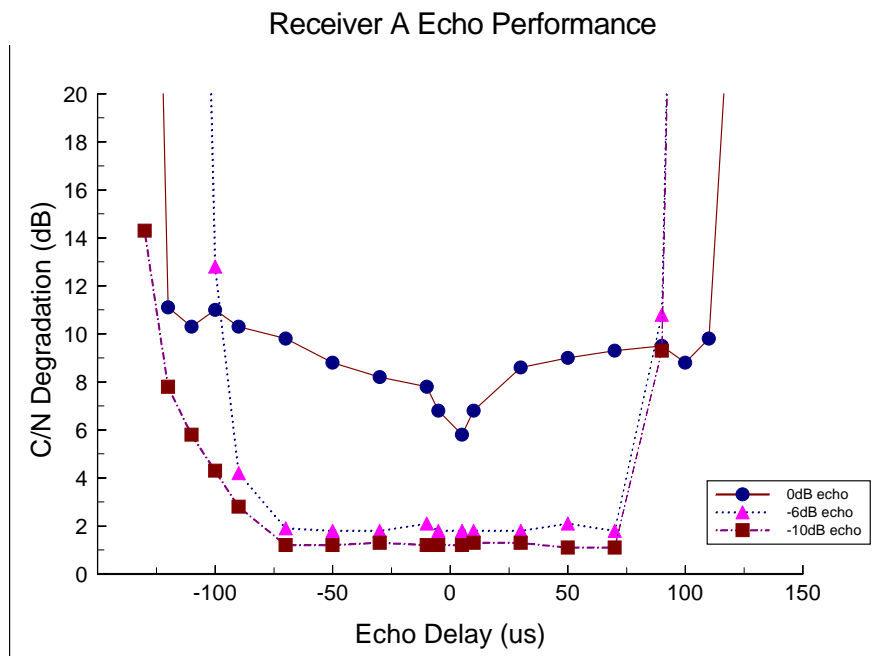
The proposed trial SFN was modelled, using the Canadian CRC-COV network planning software, to assess it's viability and the expected extent of coverage. Ideally, practical receivers should be able to cope with both pre- and post-echo signals over the full guard interval range of 128us. SFN performance would be compromised if this was not the case. The capacity of a receiver to cope with multiple signals was also seen to be dependent upon the placement of the guard interval in relation to all the available signals. Manufacturers may employ one of a number of such receiver synchronisation algorithms and these affect SFN performance. Consequently, it became apparent that some assessment should be made of available receiver performance before reception modelling could begin.

Receiver Testing

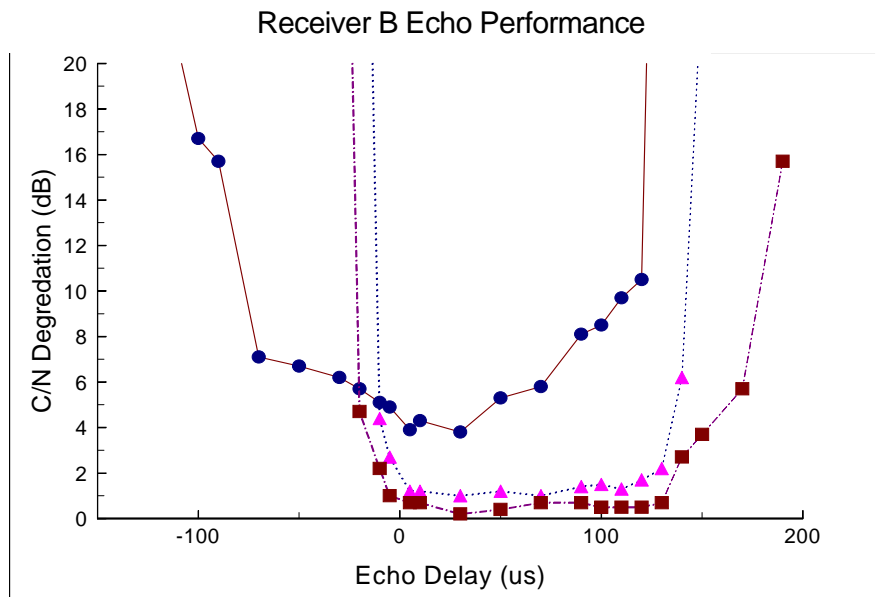
ntl assessed three receivers, each with different design characteristics. It was ntl's view that the most important receiver parameters affecting SFN performance would be the echo delay range over which the receiver operated and the resulting C/N degradation penalty. Consequently, ntl constructed a test rig using SFN equipment to estimate these factors under ideal conditions.

Receiver Echo Performance

A simple test methodology of combining two SFN signals was adopted and the attenuation of the signal level corresponding to the Threshold of Visibility (TOV) was recorded for one signal alone. The required attenuation in the presence of a second 'echo' signal was then measured to produce the same TOV. This procedure was repeated over a range of echo delays and echo levels. For convenience, the test used UHF channel 35, as performance was not expected to vary with frequency. For confirmation, Receiver A was retested using VHF channel 12 and produced almost identical results. The performance of each receiver is demonstrated below:

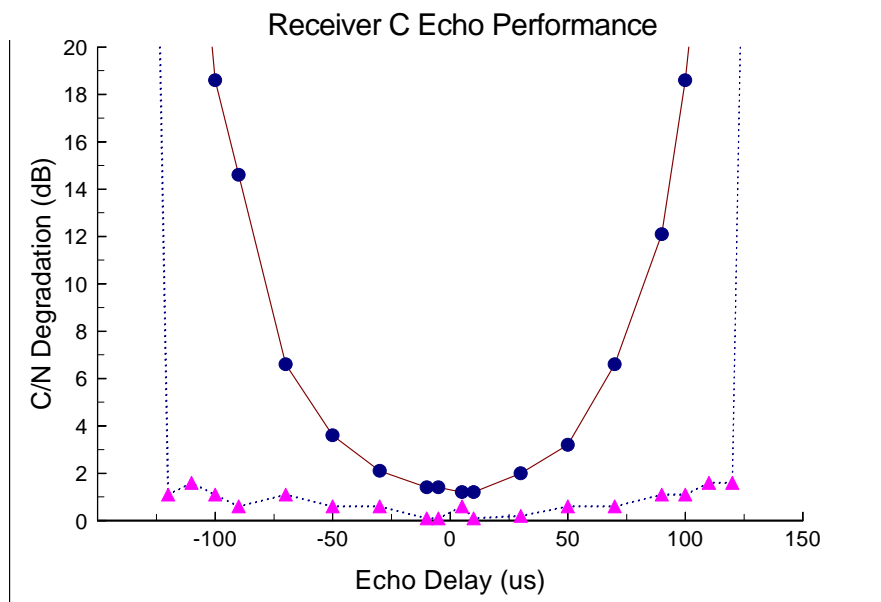


Receiver A exhibited large degradation with equal signal levels but still functioned to the edge of the guard interval. However, during lower level echos, while degradation was low, useful performance did not extend over the full guard interval.



Receiver B offered two synchronisation algorithms. The above diagram demonstrates its performance when the left of the guard interval was aligned with the strongest received signal. This receiver failed to cope with a lower level 'pre-echo' signal. However, its post-echo performance proved very good and this extended to the guard interval and beyond. This meant that the receiver could reliably be expected to operate over the delay range 0-135us.

The second synchronisation algorithm resulted in the centre of the guard interval being aligned with the strongest signal, designed to provide pre-echo capability at the expense of post-echo performance. However, this capability did not appear to function in our particular receiver and gave almost identical results to the left-aligned equaliser setting above.



Receiver C offered quite different performance to Receiver A. An equal level echo caused rapid performance degradation as delay was increased. With a lower level echo, degradation was very low and extended over almost the full guard interval. As this receiver was UHF only, it was not used in the field trials.

These results demonstrate that a practical receiver exists today which offers good SFN performance with minimal C/N degradation at up to 6dB echo levels.

Doppler Shift Performance

Each receiver was also tested for doppler shift resistance in the presence of a single 10us echo, in order to gauge the ability of each receiver to cope with vehicle and aircraft flutter in the 8k mode as required for SFN operation. The results are summarised below:

Frequency offset (Hz) Required for Less than 3dB C/N Degradation:

ECHO LEVEL	Receiver A	Receiver B	Receiver C
0	0	+4,-4	+49,-48
-6dB	+45,-47	+48,-48	+65,-65
-10dB	+62,-67	+63,-63	+76,-78

These results indicate that, at a -10dB echo level, the doppler shift performance for a current 8k mode receiver is in the order of +/-60Hz. This corresponds to an approaching object speed of 81km/h at a frequency of 800MHz or 320km/h at a frequency of 200 MHz.

Revised Reception Modelling

It was clear from the receiver bench tests that receiver echo performance varied with both echo level and signal delay. Performance was found to be highly variable between the different receivers. Consequently, to model the trial SFN, individual modelling of each receiver used needs to be done. However, while receiver performance could not be exactly modelled using the CRC-COV software, useful approximations were made.

The models used, placed the SFN signals correctly within the guard interval window for the particular receiver, but underestimated the required C/N in areas of equal signal level. Comparison of this revised modelling with actual SFN performance is treated later in the measurement analysis section.

Trial Setup

What is Where and Why?

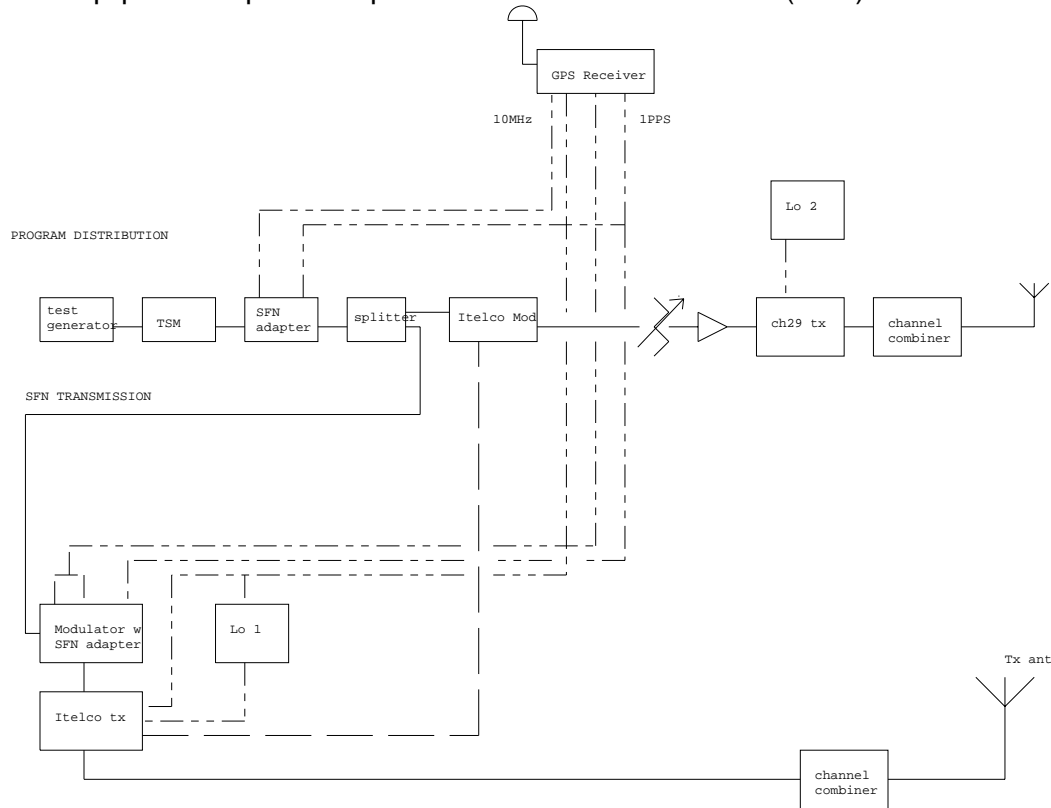
SFN Requirements

In constructing the trial network, ntl addressed the design criteria as follows:

- Frequency: Local oscillators at the transmitting sites were locked to a common frequency reference. For convenience, ntl used GPS-derived 10 MHz references.
- Time: GPS-derived 1 pulse per second clock was used to supply the modulators and head-end SFN adapter with time information.
- Data: Given the identical data requirement, that no processing equipment was allowed to insert stuffing packets to correct for bit rate variations or data clock mismatches, ntl used modulation equipment that derived its data clocks from the incoming transport stream to meet this requirement.

Main Site Setup

The equipment required to operate at Black Mountain Tower (BMT) as follows:

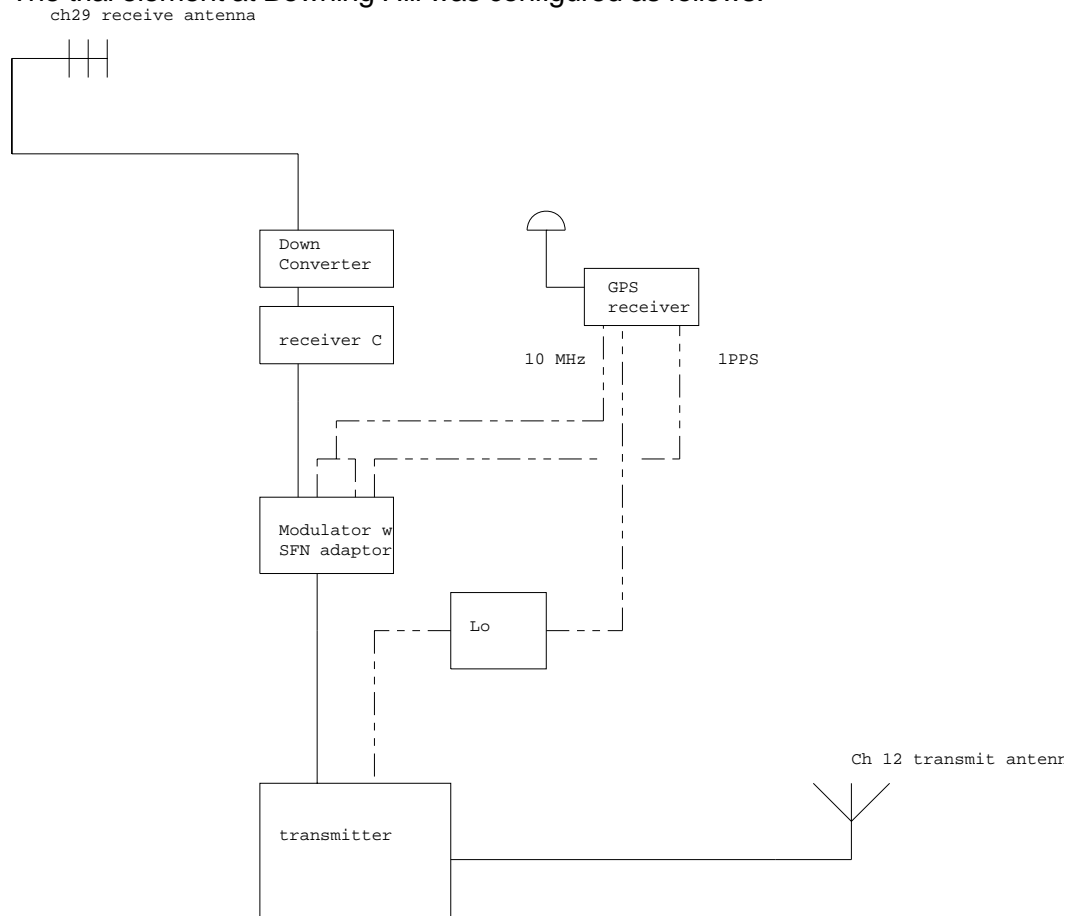


1. The MPEG source was derived from a test sequence generator.
2. The transport stream modifier (TSM) unit inserted the Megaframe Initialisation Packets (MIP) into the transport stream, as required to correctly insert the SFN timing synchronisation information within the modified transport stream.
3. The SFN adaptor derived the time from the GPS Receiver and inserted it into each MIP to convey the correct starting time for each megaframe, and hence for data timing.
4. The modified bitstream was fed to the main transmitter and to the link transmitter using a transport stream splitter.

The setup was rather unusual in that the modulator provided the signal source for the Itelco ch12 transmitter, but the Itelco modulator actually provided the signal source for the NEC ch29 link transmitter.

Second Site Setup

The trial element at Bowning Hill was configured as follows:



1. A down-converter was used to re-invert the frequency sense of the off-air ch29 spectrum because it was being transmitted inverted.
2. Receiver C was then used to demodulate the ch29 signal to provide the SFN transport stream for the transmission.
3. A modified transposer was used as the transmitter and provided about 35W RMS power for the digital signal with -35dB spectrum shoulder levels.
4. A band III panel antenna was used to transmit the signal, providing about 150W peak ERP.

Program Distribution

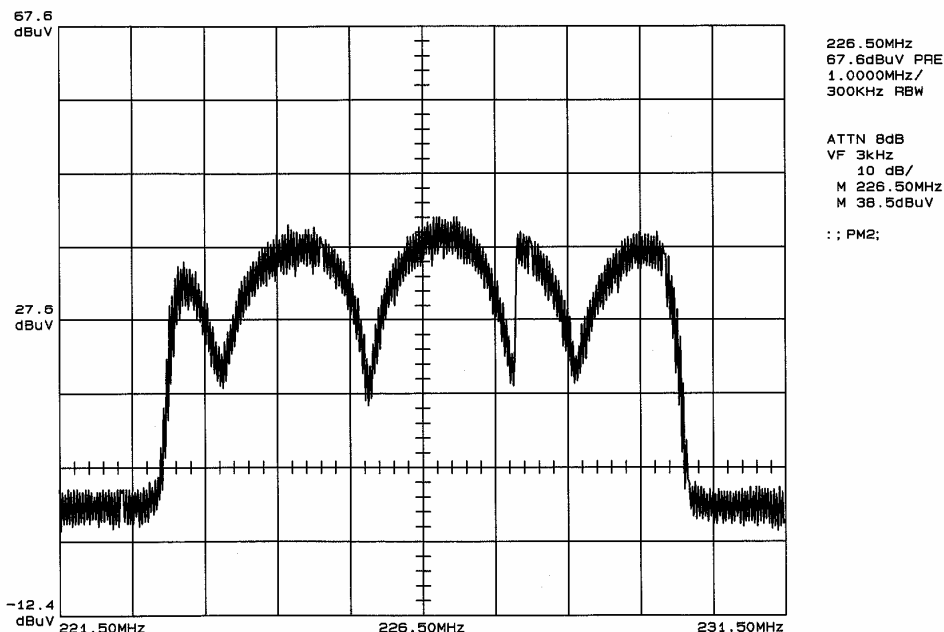
The transmitted program was distributed within the SFN using the existing ch29 UHF DVB-T transmission at BMT as sufficient off-air signal level was available at Bowning Hill. No additional satellite or microwave link was therefore necessary. The signal was generally reliable though some faults were generated by an intermittent mechanical problem within the receiver used at Bowning Hill. However, this was manageable and did not detract from the results obtained.

Program Synchronisation

Transmitted program was synchronised within the SFN using GPS receivers and NDS SFN equipment. Synchronisation stability appeared to be approximately $\pm 1\mu\text{s}$ between transmissions. This effect is believed to have been caused by the inability of the SFN adapters to track fast network delay variations caused by the receiver that was used to receive the off-air ch29 signal at Bowning Hill. However, this would be more than sufficient for a network utilising a 128 μs guard interval as is suggested for SFN use in Australia.

Network Delay Setup

Network delay was adjusted at Bowning Hill by combining the off-air Ch12 BMT signal and the transmitted Bowning Hill signal and then adjusting for approximately equal levels. The spectrum was then observed. A slightly-delayed signal will exhibit a self-fading spectral ripple corresponding to the time difference between the two signals. In a practically-observable sense, signals can be considered to be exactly synchronised when there is a complete cancellation of each signal. However, due to the synchronisation instability noted above, the most cancellation that could generally be achieved was a sweeping, beating effect with the delay difference moving in and out of exact synchronisation. An example of almost complete synchronisation is shown below:



It was clear after observing this synchronisation effect with a receiver that highly-variable reception could result. Consequently, in the design of a SFN, the areas where this occurs would need to be minimised and this would be done through appropriate adjustment of transmission delays within the network.

Trial Measurements

What was Done and How

Measurement Regime

Trial measurements were collected in two stages. During the first stage, the Bowning Hill antenna was directed mostly away from BMT in a 'signal extender' type application. ntl chose a relative transmission delay of 20us in order to avoid any self-fading effects due to close time synchronisation in the nearby Bowning township. Measurements at a delay of -80us were also taken in most locations for comparison. A typical rural band III receiving antenna was used for measurements in this stage to maximise the number of locations where successful readings could be taken.

During the second stage, the Bowning Hill transmit antenna was directed towards Yass in an 'in-fill' type application. The relative transmission delay was set to 0us as measurements were not being taken in areas likely to be subject to self-fading. A receive antenna with poorer directional discrimination was used in this stage to maximise the secondary signal.

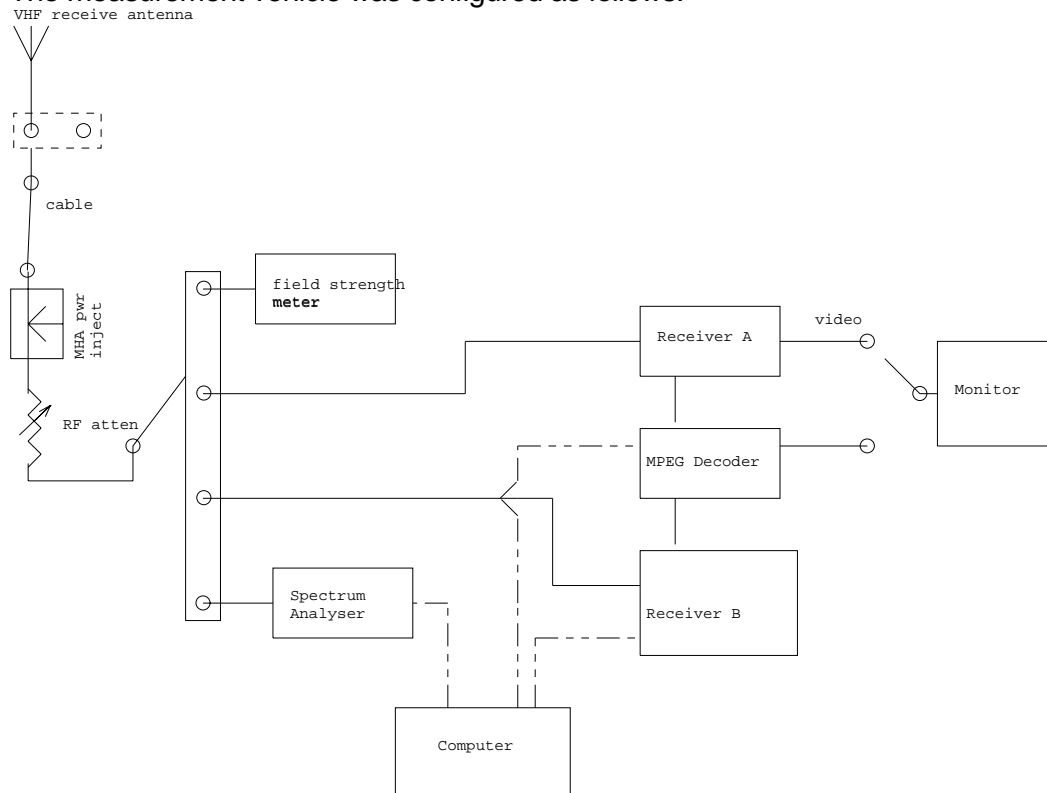
The transmission parameters were then set for each stage:

Stage	Antenna Orientation	Relative Bowning Hill Delay
Bowing Area	~310°TN	-80us then 20us
Yass Area	~150°TN	0us

Following bench testing of the receivers, trial measurements were undertaken at those locations where the performance of the receivers could be verified in the field, rather than seeking only to determine and map coverage. In addition, it was decided to measure performance with two receivers, Receiver A and Receiver B. The aim was to measure the level of signal from each transmission site and the effect of SFN operation upon each receiver. The threshold of visibility for each transmission was measured separately, and then together under SFN operation, in order to determine the success of the SFN. Measurements were undertaken using a specially equipped ntl survey vehicle.

Measurement Method

The measurement vehicle was configured as follows:



For each measurement site, the methodology was as follows:

- With both signals transmitting, the receive antenna was oriented towards the generally strongest signal.
- The signal level and margin above TOV for each receiver in this SFN mode was measured.
- With Black Mountain transmitting only, the signal level and margin above TOV for each receiver was measured.
- With Bowring Hill transmitting only, the signal level and margin above TOV for each receiver was measured.
- At each stage, unusual spectra and/or other peculiarities were noted.
- Where appropriate, repeat measurements with the receive antenna in a different direction were taken.

Trial Results

Interpreting the Measurements

Receiver Performance

Spot Checks of Receiver Echo Delay Range:

In addition to the general measurements, spot checks were undertaken at a small number of locations to verify the delay operating range of both receivers. This was achieved by adjusting the Bowning Hill delay to achieve time synchronisation at the remote measurement point, measuring the TOV with a readjusted signal delay of 20us, then varying the Bowning delay again to degrade that TOV by 3dB. These points are summarised below, and confirm the delay range behaviour of the receivers measured on the test bench:

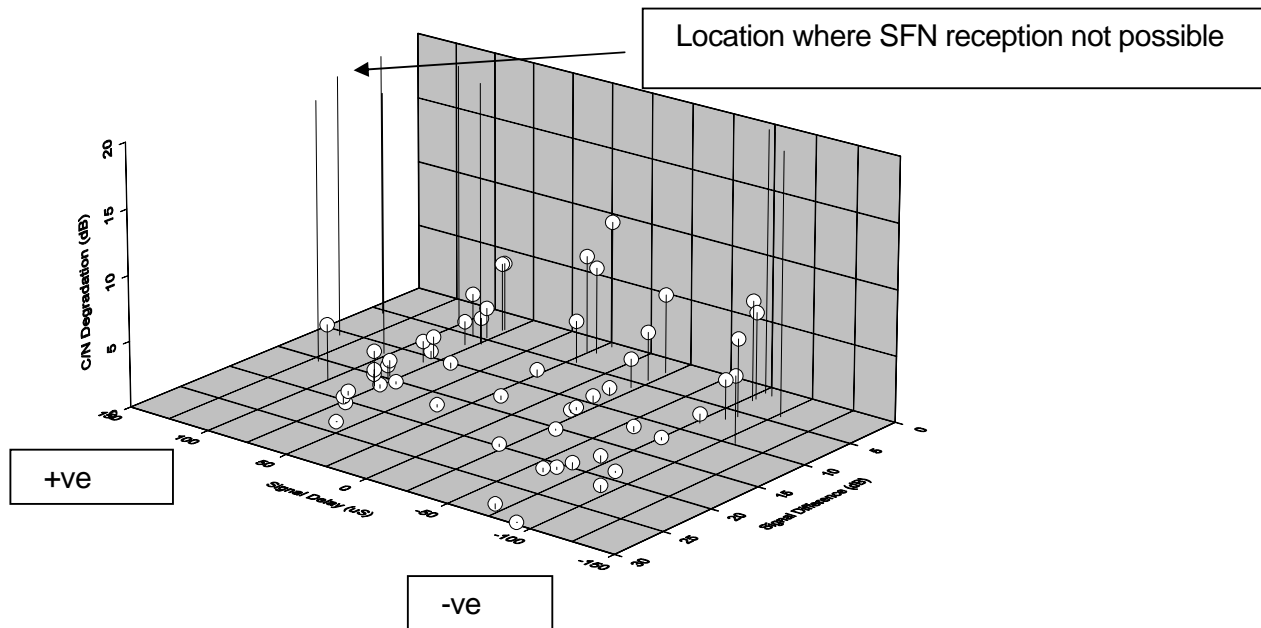
Receiver A

Bowing Delay for synch	Signal Level Difference	Local Delay Range	Receiver Delay Operation Range
97us	+10dB echo	15us to 195us	-98us to 82us
206us	-5dB echo	100us to 300us	-106us to 94us
206us	-0.5dB echo	75us to 325us	-131us to 119us

Receiver B

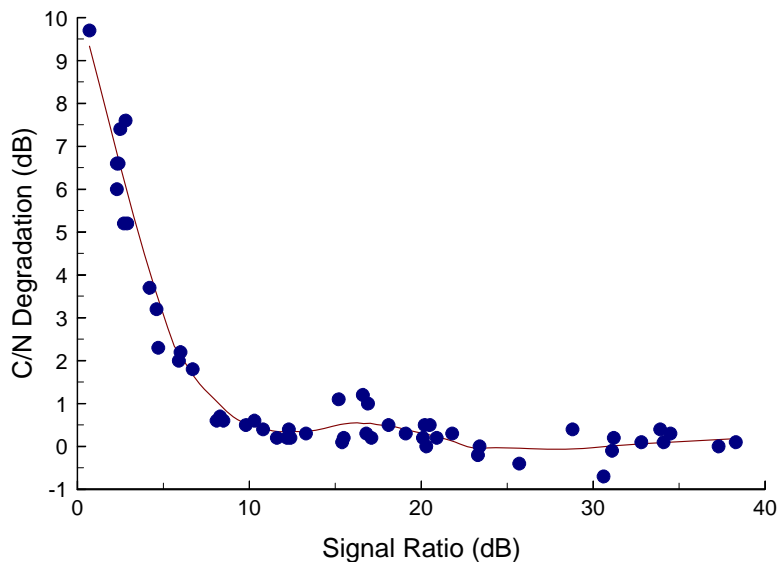
Bowing Delay for synch	Signal Level Difference	Local Delay Range	Receiver Delay Operation Range
97us	+10dB echo	-48us to 115us	-18us to 145us
206us	-5dB echo	195us to 335us	-11us to 129us

Field measurements for Receiver A are presented graphically as follows:



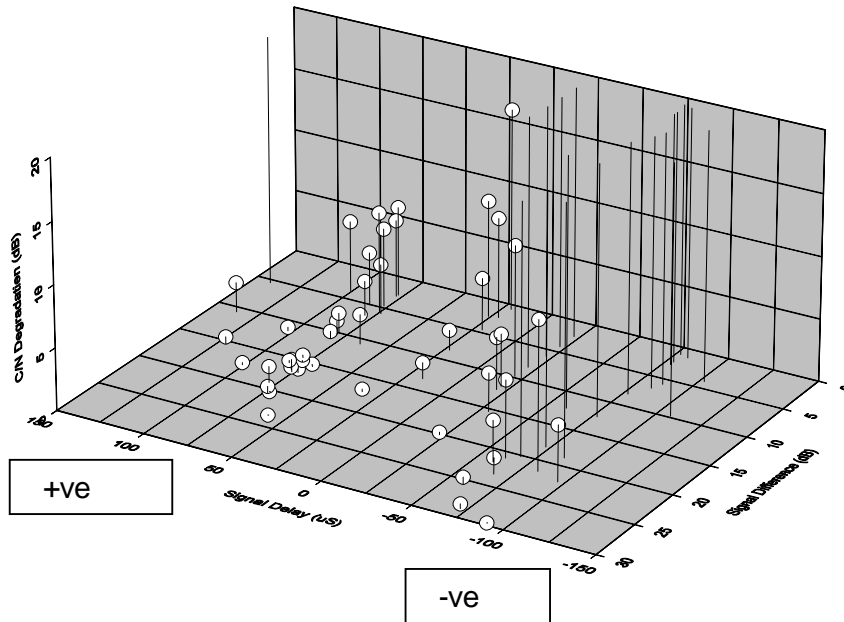
The scatter plot clearly shows a trend towards an increasing C/N requirement as signal ratios approach equality and as the guard interval is approached for Receiver A. Significant C/N degradation is clearly evident as early as $\pm 80\mu s$ or so.

Receiver A field measurements Over Restricted Delay Range ($-80\mu s$ to $80\mu s$)



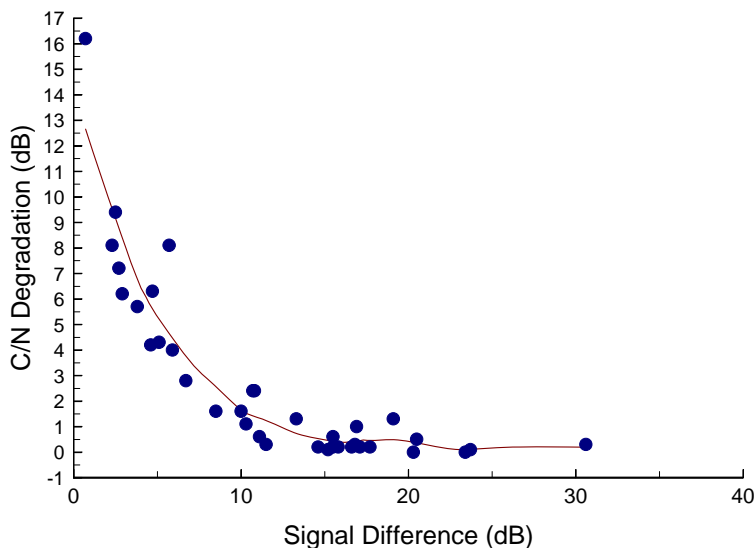
If results are restricted over the fairly linear delay range for Receiver A, a correlation can be seen between signal level difference and increased C/N requirements. The results are similar to those measured under ideal conditions as in the bench tests.

Field Measurements for Receiver B are presented graphically as follows:



In contrast to the plot for Receiver A, this plot clearly indicates the failure of Receiver B to deal with pre-echos. However, Receiver B successfully receives signals over a longer positive echo range than Receiver A.

Receiver B field measurements Over Restricted Delay Range (0µs to 135µs)



Again, over a restricted delay range, the field results show the expected trend of an increasing C/N requirement as signal levels approach equality. As in the bench tests, Receiver B exhibited less degradation with 6 or 10dB echos compared with Receiver A.

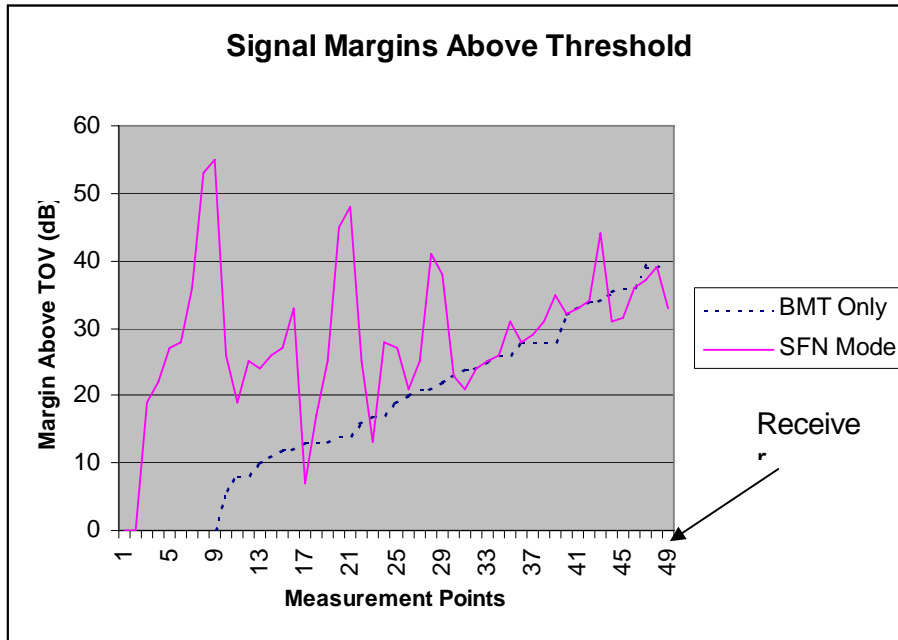
Coverages Achieved

Whilst the short length of the trial prevented measurement of the absolute extent of signal coverage, the maps on the following pages overlay the measured SFN signal margin on top of CRC-COV generated margin maps using the approximated model for each receiver.

Results for Receiver B are not presented for the Bowring area because the CRC-COV software had difficulty calculating margins in areas where the signals were very close in level and time with the particular synchronisation algorithm employed. This prevented a useful display and printing of the results.

Margin Improvement For Receiver A in the Bowring Area

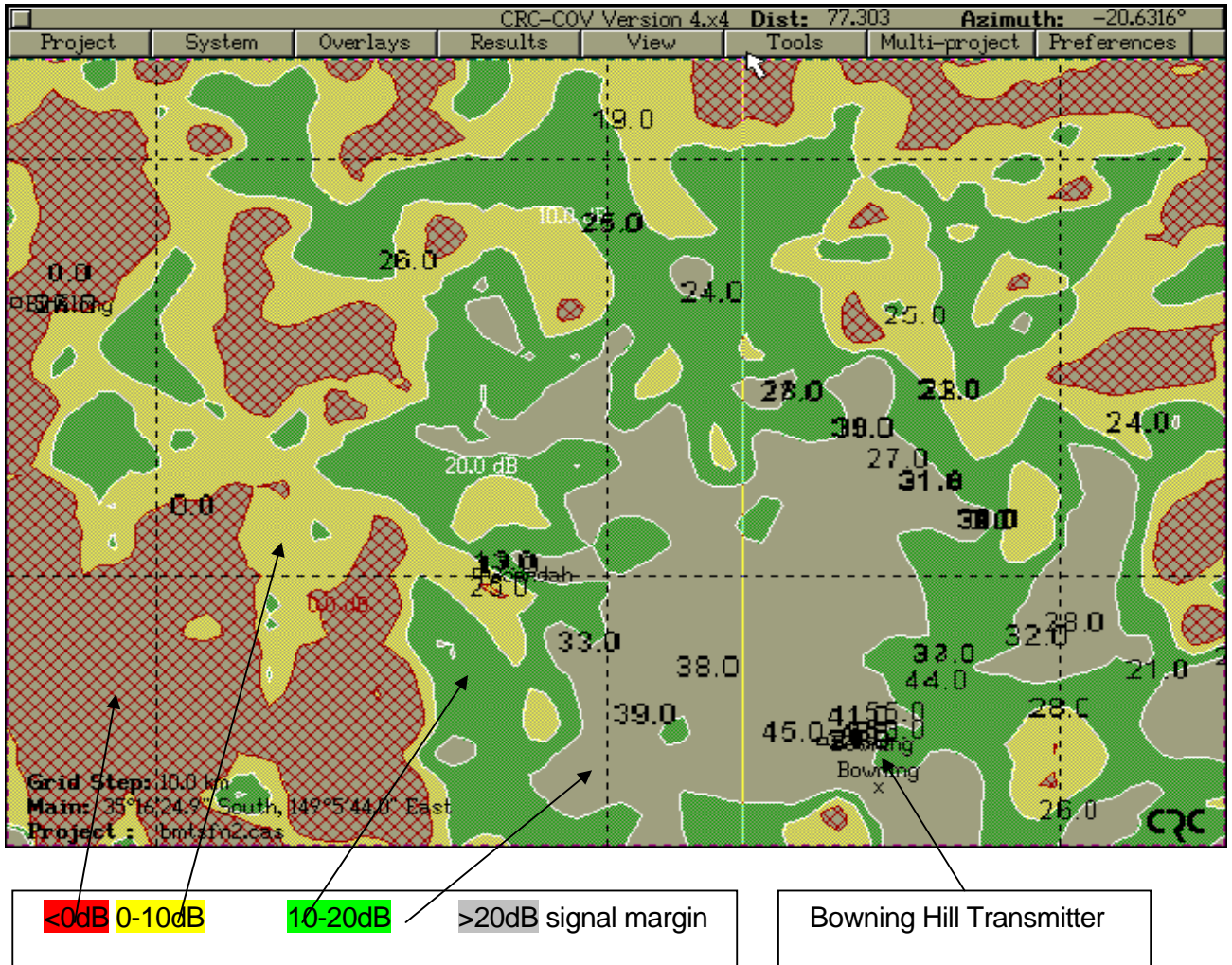
As an example to demonstrate the signal improvement due to SFN operation, the following graph indicates the signal margins at each measurement point for Receiver A in the Bowring area, for the BMT transmission only and under SFN operation.



The graph indicates significant signal margin improvement at a majority of locations due to SFN operation. Significantly, signals could not be received at only two points under SFN operation, compared with 9 points with BMT transmitting only.

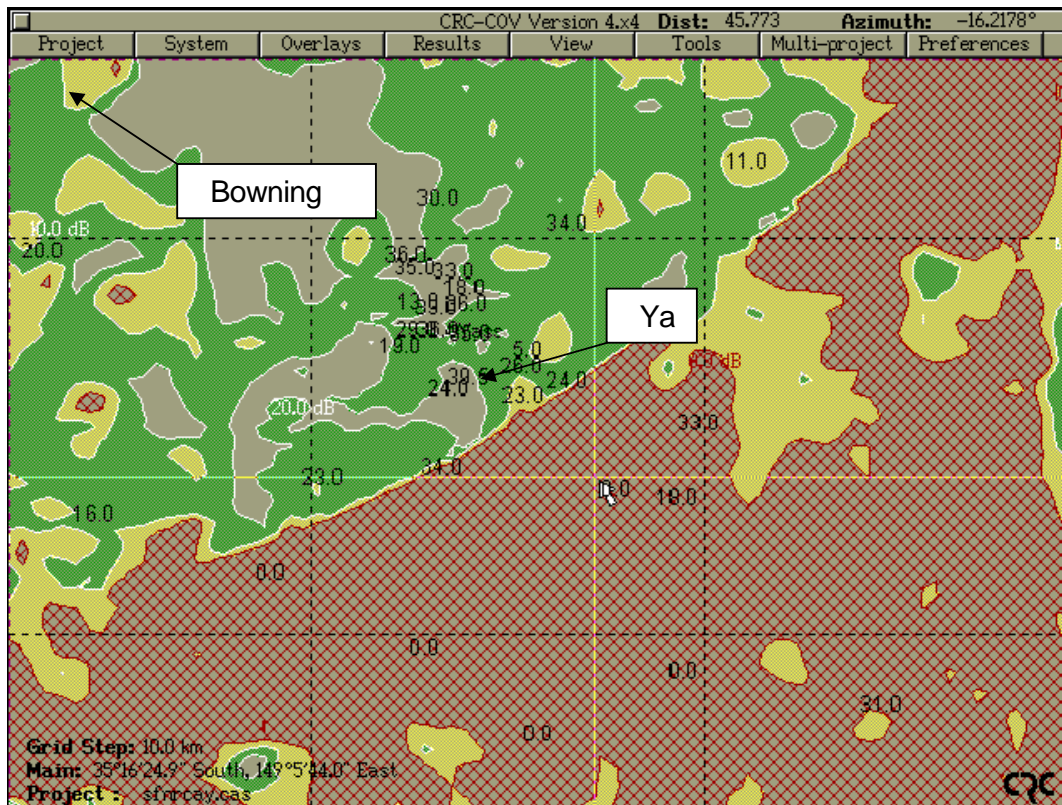
As previously indicated, the signal margin is sometimes degraded due to SFN operation if the signals are approximately equal.

Coverage Margin Comparison: Receiver A in Bowring Area
Both -80us and +20us transmission relative delay settings combined



The results using Receiver A have been combined for the two delay cases in the Bowring area. These results, both calculated and measured, are very similar due to the measured delay range of the receiver. Margins and areas of deficient coverage (in this case due to lack of outright signal level) are in reasonably close agreement with the predictions. No areas of intra-SFN interference were evident.

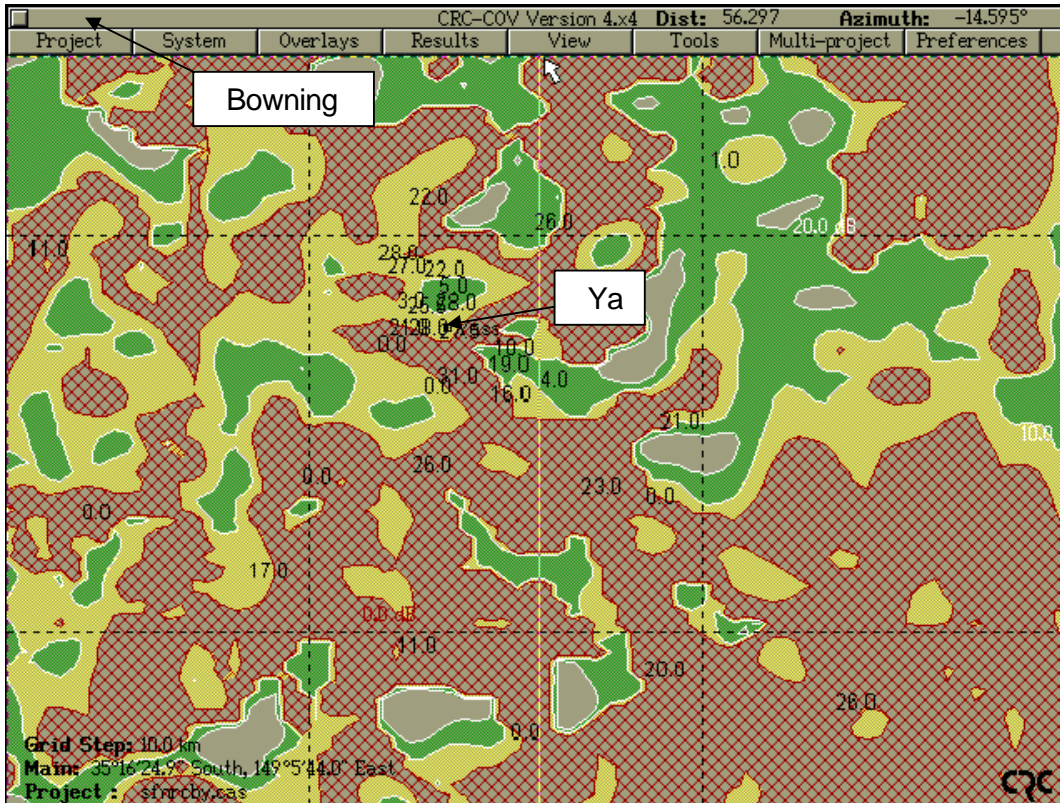
Coverage Margin Comparison: Receiver A in Yass Area



Results for Receiver A in the Yass area show reasonable agreement and the measured results support the predicted large area of interference south of Yass. This was expected and is caused by the delay difference exceeding the capability of the receiver, ie approx $\pm 80\mu s$. However, the failure transition is not as sharp in practice as anticipated, as the performance of the receiver rolls off gradually. Individual locations of successful reception in this area were caused by local obstruction of one of the signals not identified by the software modelling.

Coverage predictions indicate that if Receiver C had been used in the Yass area, together with a VHF to UHF converter, coverage would have exceeded that with Receiver A due to it's better performance with the expected echo levels.

Coverage Margin Comparison: Receiver B in Yass Area



Results for Receiver B in the Yass region show the least agreement and highly variable reception. This is a function of Receiver B aligning with the strongest signal in areas of overlapping coverage. In the Yass area the strongest signal changed rapidly. Where Bowning proved the stronger signal, the receiver was likely to fail as BMT was received as a pre-echo. Where BMT proved the stronger signal, Bowning was received as a post-echo and reception was then generally successful.

Conclusions

Implications for Spectrum Planning

Trial SFN Performance

The SFN worked well with Receiver A when the Bowning Hill transmit antenna was directed away from the main site (towards Bowning). No interference was evident and the coverage margin was very good.

The SFN worked with Receiver A when the Bowning transmit antenna was directed towards the main site until areas were reached where the time delay between the signals exceeded the capability of the receiver. A large area of interference was then evident south of Yass. This area of interference would be much smaller given more receive antenna discrimination and a receiver capable of operation over the whole of the guard interval.

The SFN did not work consistently with Receiver B. Successful reception depended upon which transmission site provided the strongest signal and hence whether the weaker signal was seen by the receiver as a pre- or post-echo.

Receiver Performance

The two receivers used in the field trial operated closely in agreement with the previously-undertaken bench test results. Consequently the results reflect the following observations:

- Performance varied significantly between the different receiver implementations.
- Increased C/N requirements are necessary in areas of approximately equal signal level.
- Unlike DAB, it was evident that there is no possibility of 'network gain' when using the 64QAM modulation mode (that proposed for DTTB use in Australia). The presence of a second signal degrades the receiver's single signal performance.
- The receivers used did not necessarily operate over the full time delay range desired (ie the guard interval range of $\pm 128\mu\text{s}$), their performances depending on their design characteristics. The delay range capability also varied with the relative level of the echo signals. One receiver was unable to cope with 'pre-echo' signals due to the way it synchronised to the available signals.
- Improved receivers need to be available to exploit the full potential of DVB-T SFNs.

Planning SFNs

The observations regarding the particular receivers used imply certain potential requirements for the planning of SFNs.

- Network planning software must be able to implement complex receiver models to support the C/N requirements and general behaviour of receivers. Some current software is capable of useful approximations and it is expected that no major obstacle exists in developing software with more accurate models.
- Areas where signals arrive together approximately equal in both level and time, should be avoided as fading can occur. This is a difficult effect for software to model due to its wideband nature.
- To avoid unexpected intra-SFN interference, especially in large-area SFNs, accurate propagation modelling and terrain databases need to be used.
- Planning should be detailed in order to identify worst-case deficient areas.

Viability of Large Area SFNs

Large-area SFNs are viable given careful network planning and use of properly designed receivers. The following factors enhance the success of any large area SFN:

- Selection of secondary sites directed away from the main site and using directional transmitting antennas will help ensure the available signals are kept within the guard interval.
- Minimising the ERP at secondary sites where it is directed towards the main site. This will help ensure available signals are kept within the guard interval.
- Use of properly designed receivers that will cope with both pre- and post-echos over the whole of the guard interval.
- Optimising network delays to minimise signal delay differences in areas where signal levels approach equality and so avoiding areas where signal cancellation may occur.
- Maximising the antenna discrimination used in receiving installations will help reduce intra-SFN interference in areas where it does occur.

Large-area SFNs will be most successful in applications where low power 'coverage extenders' are required and where power is directed away from other SFN-related sites. In that case it is easy to ensure that relative signal delays do not extend beyond a receiver's capability. For large-area SFNs where large "in-fill" coverage is required, the relative signal delay may extend beyond a receiver's capability, causing failures in areas where signals levels approach equality.

Endnote

The ntl trial demonstrated that large area SFNs are viable and offer the potential for more efficient use of spectrum. SFN design requires careful planning and use of appropriate modelling tools. Their use will depend upon manufacturers developing appropriate receivers for use in the marketplace.

To ensure SFNs can be utilised in Australia, appropriate modification of the relevant standards may be required.