®

Digital Audio Broadcasting

Digital Radio Broadcasting in Canada
A strategic approach to DRB implementation

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While digital sound broadcasting tends to be regarded as a European interest, much valuable work is being done in other countries, and in Canada in particular.

The present article presents the wide–ranging collaborative study programme under way in Canada.

The results will be of interest in Europe, too, since thestudies include detailed consideraion of the 1500 MHz band, which has so far received relatively little attention elsewhere, at least in comparison to the research effort deployed at frequencies near 200 MHz.

1. Background

In 1989, Canadian broadcasters serving on a federal government advisory committee on broadcast technical research projects began to promote the concept of a national strategic plan to foster the conversion of our radio broadcasting system from the current analogue mode to digital. A key element of this plan included obtaining full tri–lateral cooperation involving the public and private broadcasting sectors, as well as federal government departments and agencies.

This joint planning and research proposal dovetailed with work already being done on Digital Radio Broadcasting (DRB) within the Canadian Broadcasting Corporation (national public radio), the Canadian Association of Broadcasters (representing private broadcasters), and the former Department of Communications (now part of Industry Canada). The basic idea was accepted in principle by all parties and an ad–hoc organizing group was created.

Observing developments in DRB technology in Europe, the group decided to sponsor live DAB demonstrations in Canada as a means of stimulating interest. This first close look at digital radio in Canada was carried out in 1990, with the cooperation of the Eureka 147/DAB Project. It involved installations in four cities that permitted test transmissions and demonstrations at 800 MHz.

Early in the preparations, it was decided to concentrate first on the terrestrial services, to be followed by the satellite services some time in the fututre when a sufficient number of receivers became

Original language: English
Manuscript received 3/1/1995

available. This article thus focusses on the terrestrial DRB.

1.1. Planning organization

The high degree of enthusiasm for DRB that was generated by this project led to the eventual creation of a planning organization consisting of three autonomous but closely coordinated groups. These are the Task Force on the Introduction of Digital Radio, the Digital Radio Coordinating Group of the Joint Technical Committee on Advanced Broadcasting (JTCAB), and Digital Radio Research Inc. (DRRI).

The Task Force was created in 1992 by the federal minister responsible for communications and is an umbrella advisory body on all matters concerning DRB. In reality, it is Canada's "Platform Group" on DRB and deals with the high–level policy and regulatory issues.

JTCAB is a technical advisory group, providing expert advice on all facets of new broadcast technology. It conducts all the DRB engineering tests and evaluations now being undertaken.

DRRI is a private DRB research company, jointly owned by the Canadian Broadcasting Corporation and several large private radio broadcasting companies. It owns and operates all of the country's experimental DRB hardware and conducts public demonstrations of the technology. In short, it is the "operating arm" of the public/private/government cooperative. Financing for DRRI's work comes directly from the owner groups and from government research grants.

1.2. Experimentation to date

Immediately prior to WARC–92, the JTCAB conducted the first field tests of L–band DRB, using Eureka 147/DAB hardware. This was undertaken to generate technical support for Canada's WARC–92 position, which recommended a new allocation of spectrum for DRB in the region of 1450 MHz. Our DRB vision calls for the establishment of a mixed system, whereby both satellite and terrestrial services would co–exist in the same band.

Following the successful results of WARC–92, where 40 MHz of new DRB spectrum was allocated on a world–wide basis, Canada moved forcefully ahead with its plan to refine its strategy. To date, DRRI has constructed experimental L–band DRB transmitters in our two largest radio markets, covering 25% of the country's total population. Two additional cities are under consideration for 1995. Local stations are participating actively in both promotion and technical experimentation at each DRB site.

1.3. Canada's DRB rationale

Historically, Canada has been a follower rather than a leader with respect to the development and utilization of new broadcast technologies. Being a leader has its risks, but remaining a follower means giving up a significant degree of control over the future of one's industry. In the present case, our broadcasters wanted to take the lead and thus ensure that a full range of technical options could be pursued for radio in the next century.

Canada's aggressive position on DRB originates from a concern that Europe has developed an elegant technology, but that its initial implementation plans were considered to be unsuited to North America. On the other hand, the US concept of implementing DRB in the present AM/FM bands would place unacceptable constraints on these new services. In particular, Canada considers that narrow–band DRB would severely limit the potential of this new technology to do all the things necessary to rejuvenate radio in the 1990s and beyond.

The key factors leading radio broadcasters to conclude that a conversion to digital transmission is vital are as follows:

- Broadcasting is part of Canada's national electronic communication infrastructure, which is converting rapidly to the digital mode.
- Analogue AM/FM delivery cannot provide the quality that the public has come to expect, due to the increasingly widespread use of CDs and other digital audio devices.
- Digital techniques permit much more reliable off–air service to a major audience component – the portable and mobile listener.
- Radio studios are moving to digital for operational reasons and it makes sense to deliver this high quality all the way to the listener.
- Digital transmission permits "pay radio" and has extra capacity for auxiliary data transmission, thus providing potential new revenue sources for broadcasters.
- Cable operators are poised to deliver high–quality, very reliable digital signals to local radio audiences.

To ease the transition to DRB for both the public and the broadcasters, the following general policy principles have been advocated:

- Digital radio services should be designed primarily as replacements for existing local terrestrial AM/FM services and not as a new "tier" of radio service.
- Existing local AM/FM services should each be provided with a new transmission channel for a parallel digital service. Simulcasts may have to continue for 10–15 years.
- Terrestrial DRB service areas should closely approximate the principal market areas of existing AM/FM stations.
- Adequate capacity for auxiliary data services should be included within the data multiplex.
- A future satellite component should be planned for during the implementation of the terrestrial component.
- A wide–band transmission technology should be utilized, so as to ensure CD quality, high signal reliability, and maximum spectrum efficiency.
- New wideband digital transmissions should be implemented in the L–band spectrum (1452–1492 MHz) that was allocated for digital audio broadcasting virtually worldwide at WARC–92.

The latter two proposals are very controversial, especially internationally, and require some explanation. Canadian broadcasters have supported the choice of a wide–band DRB service, using L–band spectrum exclusively, because of the following considerations:

- It permits signals with much wider bandwidth, thus providing superior audio quality overall, much improved reception reliability, and virtual immunity to multipath.
- It ensures that new digital services cannot possibly interfere with current AM/FM services during the transition period.
- It permits a terrestrial, satellite, or mixed services approach by any country and provides for economical, shared–cost implementations.
- It uses less power (per service) than FM, and permits extensive control over the shape of coverage areas.
- It has the capability of providing considerable auxiliary data capacity, which will allow radio broadcasters to be part of the future "information highway", providing a robust point–to–multipoint data distribution system especially suited for data services requiring mobile and portable reception.
- L–band appears to be the only common denominator with respect to DRB implementation in all countries (except the USA), thus ensuring that receivers that will tune to this band will be produced in large quantities.

The Task Force accepted these principles, and has developed a series of recommendations to the federal government as to how best to achieve them. Key among these is the requirement to provide each existing AM and FM licensee with the L–band DRB channels required for the migration of its services over an extended period. Other important recommendations concern the specific arrangements for "duplicating" AM and FM coverage and certain licensing matters, such as the issue of control when shared transmitters are used.

These principles are being used in the preparation of the allotment plan which is described in *Section 4*. Before starting the planning process, however, system specifications and performance had to be identified and analysed through simulation activities and field measurements and trials. These are described in the following two sections.

2. Canadian studies on system performances

When Canadian broadcasters examined the characteristics of the Euraka/147 DAB system, it became clear to them that it held the potential to meet many of their requirements and expectations for a terrestrial/satellite sound broadcast system of the future. The system was then tested in the field and in the laboratory. The laboratory tests included a series of simulations designed to acertain optimum values for a number of system parameters.

2.1. Parametric study of the COFDM emission scheme

Some preliminary results of a parametric study on the COFDM emission scheme which has been performed by computer simulation are presented here, leading to the parameter values best suited for implementation of a mixed terrestrial/satellite service at 1.5 GHz.

2.1.1. Computer simulation model

General model

A block diagram of the model used for the analysis and simulation of the COFDM scheme is shown in *Fig. 1*. The data source generates a pseudorandom binary sequence. The information bits are then error protected by means of a convolutional encoder.

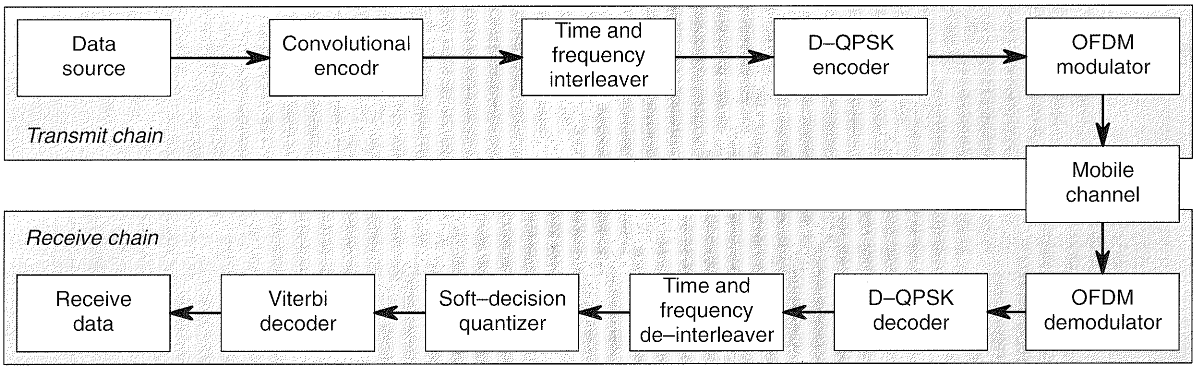


Figure 1
General model of the DRB system.

After being time and frequency interleaved, the bits are paired into di–bits and phase encoded differentially. The OFDM modulation is finally performed by means of an inverse fast Fourier transform (IFFT). After being processed through the mobile channel, the received OFDM signal is first demodulated with an FFT. The information on each subcarrier is then differentially phase decoded and de–interleaved in frequency and in time. The output of the de–interleaver is quantized before being fed to the Viterbi decoder.

Perfect synchronization and perfect (brick–wall) filtering were assumed in the simulations reported here. Effects of automatic gain control, phase noise generated in receiver local oscillators as well as non–linearities in transmit or receive equipment have not been considered. As the model so far represents a perfect implementation of the COFDM transmitter and receiver, the results represent the best possible performance for the given channel distortions.

Mobile channel models

Both terrestrial and satellite mobile channels have been simulated. The model of the terrestrial mobile channel consists of approximately 40 paths each having a fixed delay t_i, a fixed Doppler shift f_i and equal relative attenuation which corresponds to a given multipath power delay profile. Following the fading process, white noise is added to the signal prior to demodulation.

The model of the mobile satellite channel is essentially a Rician fading process which includes a direct path and a Rayleigh fading path with a fading rate that can be set to different values. In addition to the multipath channel characteristic, additive white noise is combined with the signal after the fading process.

2.1.2. Simulation discussion and results

The COFDM parameters investigated were the time interleaving depth, the number of soft decision quantization levels, the constraint length of the convolutional code and the performance of Mode III in mobile satellite channels.

Time interleaving depth

The purpose of this first series of simulations is to determine the optimal time interleaving depth value. Simulations were performed with Mode III in both typical urban (TU) and rural area (RA) mobile terrestrial channels at vehicle speeds of 18 and 145 km/h. The E_b/N_o values required to achieve a bit error rate (BER) of 10^{-4} were determined as a function of the time interleaving depth. This latter parameter was varied from 48 to 768 ms. The results show small degradations (at most 1 dB in the RA channel) as the time interleaving depth is reduced from 768 to 384 ms. Below 384 ms, the degradation increases rapidly in both channels. A time interleaving depth value of 384 ms is thus a good compromise between delay and performance.

Soft decision quantization levels

This series of simulations is designed to assess the degradations in performance resulting from a reduction in the number of levels used to quantize the input to the Viterbi decoder. This parameter has an impact on the complexity of the Viterbi decoder. Eight quantization levels is the optimal choice in the additive white Gaussian noise (AWGN) channel, but may not be sufficient in a mobile channel. In order to provide some answers to this question, simulations were performed in both the TU and RA mobile channels as well as the AWGN channel. A vehicle speed of 72 km/h was used in the mobile channels. The total symbol duration was 156.25 ms (Mode III) and the time interleaving depth had a value of 384ms. The E_b/N_o values required to achieve a BER of 10^{-4} were determined as a function of the number of quantization levels. This latter parameter was varied from 2 (1 bit/sample, hard decision) to 32 (5 bits/sample). The results show no significant increase in the value of E_b/N_o as the number of quantization levels is reduced down to 8 in the AWGN channel and down to 16 in both TU and RA channels. Below these two values, the degradation increases rapidly. Similar results were obtained at higher vehicle speeds. A quantizer with 16 levels (4 bits/sample) is thus optimal in mobile channels. A quantizer with a higher resolution is required in mobile channels (as compared to the AWGN channel) to retain the information contained in the large fluctuations of the received signal envelope.

Convolutional code constraint length

In this series of simulations, the effect of reducing the constraint length of the convolutional code from the proposed value of 7 was determined. The complexity of the Viterbi decoder grows exponentially with the constraint length value. The curves of BER versus E_b/N_o were measured in both the TU and RA mobile channels at vehicle speeds of 18 and 200 km/h and for constraint length values of 5 and 7. The total symbol duration was 156.25 ms (Mode III) and the time interleaving depth had a value of 384 ms. Results for the TU channel indicate that reducing the constraint length from 7 to 5 causes a degradation of approximately 1.5 dB at a BER of 10^{-4} and a vehicle speed of 18 km/h. The degradation reaches approximately 2 dB at a speed of 200 km/h for the same BER value. Similar results were obtained in the RA channel.

Performance of mode III in mobile satellite channels

The purpose of this simulation was to assess the performance of the Mode III parameters in mobile satellite channels. The BER vs E_b/N_o curves were measured in Rician channels with *K*–factor values of –10 and –5 dB. The vehicle speed was set to 72 km/h so that the maximum Doppler spread associated with the Rayleigh fading was f_{max} = 100 Hz. A Doppler shift (f_a) of 0 Hz (corresponding to a satellite elevation angle of 90°) and 50 Hz (corresponding to a vehicle moving at 72 km/h towards a satellite at an elevation angle of 60°) was applied respectively to the direct path. The results indicate that with a *K*–factor of –10 dB, the E_b/N_o value needed to achieve a BER of 10^{-4} is 8 dB for a satellite elevation of 90° and 8.5 dB for an elevation of 60°. These values increase to approximately 13.3 and 14.5 dB respectively when the *K*–factor is increased to –5 dB.

2.2. Transmission mode

The transmission mode to use at 1.5 GHz is very important in Canada's studies of the optimum DRB system parameters. The modes in the Eureka 147/DAB system were decided upon prior to WARC–92 and hence were not optimised for operation at 1.5 GHz. Now that the WARC–92 has allocated the 1.5 GHz band for DRB essentially on a world–wide basis, it would be very beneficial, and possibly even necessary, to optimize the transmission mode for operation at 1.5 GHz in order to achieve world wide acceptance of the Eureka 147/DAB standard.

The choice of the optimum transmission mode at 1.5 GHz is based on the trade–off between the probability of the service being affected by the Doppler spread of the channel at high vehicle speed when the symbol period is long (due to the close proximity of the carriers in the frequency domain), versus the disadvantage of a short guard interval in the time domain which would restrict the use of on–channel repeaters to shorter separation distances, thus requiring more on–channel transmitters to achieve a given coverage. This trade–off between the high availability of service for vehicles moving at high speed and the cost of implementing a DRB transmitter network, is very complex. The conclusions that are developed here are based on our experience in the field with the operation of the Eureka 147/DAB system at 1.5 GHz, on measurements on the equipment using a hardware channel simulator, as well as extensive computer simulations.

The use of single frequency networks (SFN) has long been recognised as a key feature of the new modulation scheme (i.e. COFDM) proposed in the Eureka 147/DAB system. This important feature was clearly identified in the case of VHF use, and to a lesser extent in the case of the higher UHF bands. Since WARC–92 has allocated the 1.5 GHz band, almost worldwide for DRB, this band has became the focus of the DRB work in Canada. The search for this optimum mode of operation involved striking a suitable balance between system failure caused by channel impairment in the frequency domain (Doppler spread), and failure due to temporal channel impairment (echo spread including presence of widely separated active echoes in SFN operation). Furthermore, in our current approach for planning DSB at 1.5 GHz, SFN operation has become a critical element in meeting the requirements.

Our findings, so far, indicate that, for 50 km transmitter separations in an SFN, even though a guard interval duration of 166.7 μs is required if three transmitters are to be included within the guard interval zone, values as small as 90 µs may be sufficient to minimize the intra–SFN interference limitations, depending on the environment and the type of terrain. The suitable balance between guard interval duration and Doppler spread limitation would then tend to fall somewhere between Mode II, as proposed in the draft ESTI specification, and a new "Mode 1.5" which is a logical extension of Mode I with half its symbol duration. This new reference "Mode 1.5" is easily defined as fitting exactly between the current Modes I and II in the geometrical progression of the currently proposed three system modes. The guard interval for this Mode 1.5 would be about 125 sec, double that of the current Mode II.

Our findings are that the desired mode falls close to either Mode II or the new Mode 1.5 respectively, depending on whether the emphasis is on the availability of the service to vehicles moving at high speed, or on the minimum cost and maximum flexibility in implementing a SFN transmitter network. Even though the optimum operating point for 50 km transmitter separation is somewhere between this new Mode 1.5 and the current Mode II, it may be easier from a practical point of view to simply include Mode 1.5 as part of the emission system. If only Modes II and 1.5 could be provided, the choice of mode could be made by the system operator depending on whether the broadcasters need reliable SFN operation with fewer transmitters or sustained service availability at high vehicle speed.

2.3. Technical evidence for choice of transmission modes

2.3.1. Guard interval considerations

Computer simulations

When the transmitter separation is too large for the guard interval provided, certain zones within the service area become affected by intra–SFN interference. This interference is due to the excessive delays of some of the received SFN signals which then have a destructive effect rather than providing network gain. The topography of the service area determines to a great extent the probability and the size of the zones affected by intra–SFN interference. In order to appreciate the severity of the problem, computer simulations were conducted with three–transmitter SFN systems in six Canadian cities characterised by their varied topographic features. In each case, the transmitter separation was about 50 km. The simulations were also conducted for a reference case using augmented prediction curves from ITU Recommendation 370 assuming a flat terrain with a 50 metre terrain roughness factor.

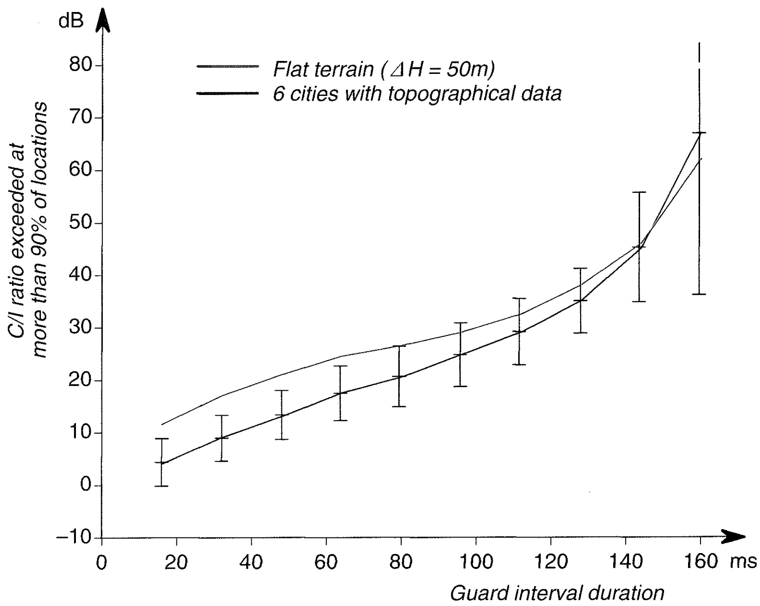


Figure 2
Relative level of interference caused by SFN networks, as a function of the guard interval.

Fig. 2 shows the results of this exercise. The ordinate values represent the carrier to intra–SFN interference ratio that is exceeded for more than 90% of the locations within the service area, for different values of guard interval. One of the curves is the reference case obtained with the curves of Recommendation 370, assuming flat terrain and a roughness factor h= 50m, while the second curve gives the average and the standard deviation values (σ) obtained by using the specific terrain elevation data in the field strength predictions for the six cities. These curves show that for 50 km spacing, larger guard interval values provide a significant increase in interference margin to mitigate intra–SFN interference. For example, a 17 dB difference is noted between 62.5 µs and 125 µs on the six–city average curve. As is to be expected, the C/I values tend to infinity for guard interval values of 166 µs and beyond since the signals from all transmitters then fall within the guard interval zone.

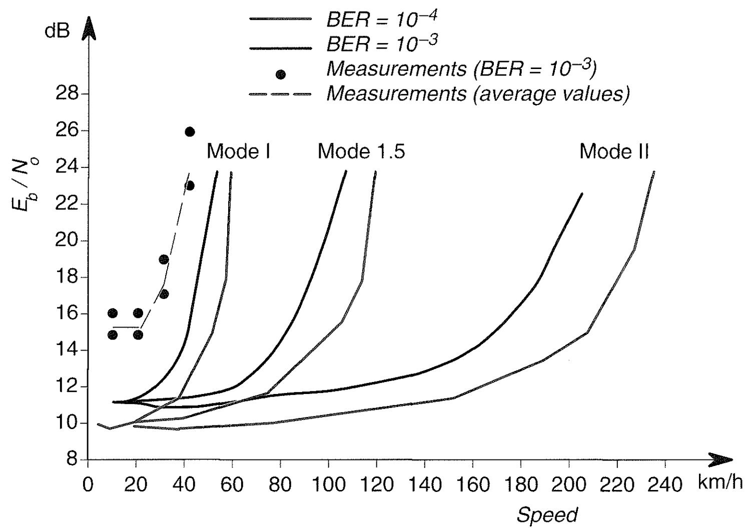
These results of computer simulations show that there would be considerable benefits to be gained in terms of improved coverage and consequently reduction in ERP requirements from an increase of the guard interval beyond that provided by Mode II.

Field measurements

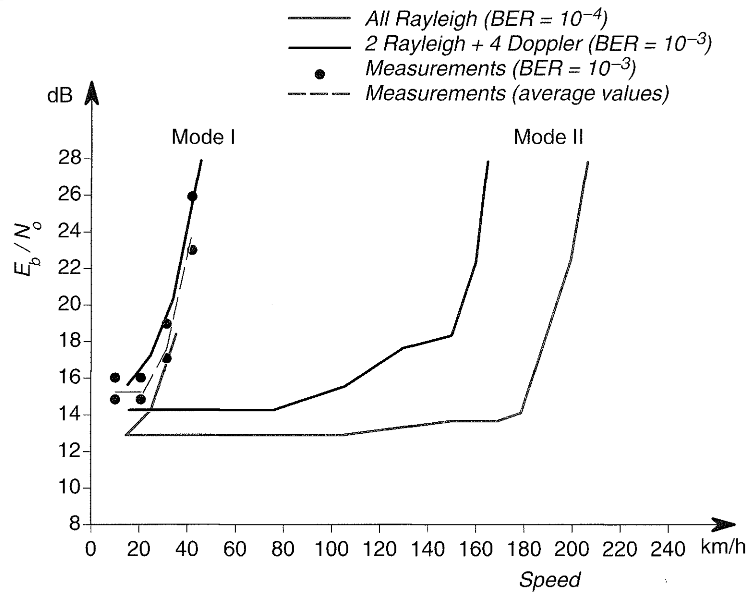
Based on limited coverage tests performed on the Barrie–Toronto 82 km SFN, and more recently on the Montreal–Rigaud–Lac Echo (53 km) SFN, it was found that the occurrence of outages caused by interference resulting from active echoes from widely spaced adjacent transmitters, arriving outside the guard interval with sufficient relative power to cause outage, was very dependent on the width of the guard interval. Although it is expected that these outage occurrences can, in some cases, be corrected by optimizing the SFN parameters (e.g., ERP, EHAAT, the relative signal delays, the use of transmit antennas with directional radiation pattern or the addition of low–power local gap fillers), it is found that a limited guard interval can place significant engineering constraints in implementing large area SFNs and achieving high coverage availability. For example in the Barrie–Toronto field tests, which used 2nd–generation Eureka 147 receivers employing a 32 μs (Mode III) guard interval, it was estimated that the number of measured outages resulting from insufficient guard interval would have been reduced by 70% by using a 64 μs guard interval. Indications are that a larger guard interval than Mode II would greatly improve the coverage without having to require special engineering measures such as indicated above with the resultant savings in capital and operating costs.

Figure 3
Results of study of Doppler spread in an urban channel.

(a) Simulations and field measurements.



(b) Laboratory and field measurements.



To summarize, the use of a larger guard interval minimizes the design constraints for SFN implementation, improves the efficiency of SFN operation at 1.5 GHz, maximizes the flexibility in locating the transmitters in SFNs and reduces the need for additional on–channel transmitters to provide the required service availability. In the case of the use of coverage extenders, where the signal is picked up off–air, the width of the guard interval is even more important since the interference–free distance between omni–directional re–transmitters is half that needed in SFNs.

2.3.2. Doppler spread considerations

An increase of the guard interval duration will, however, tend to make the system less immune to the effects of channel Doppler spread effects and equipment frequency stability.

Computer simulations

Computer simulations were carried out, based on the parameters of Mode II and the new Mode 1.5, and the results are given in *Fig. 3a* and *4a* for the TU and RA cases respectively. In all cases, Rayleigh fading (classical U–shaped Doppler spectrum) was used on all paths. Because of the Rayleigh fading and the fact that there is no line–of–sight path, this actually represents a difficult condition for the rural channel. The signal amplitude on each of the paths was defined according to the COST 207 model and actual field measurement results. As indicated on the graphs, these results correspond to BER values of 10^{-3} and 10^{-4}. It is felt however, that the level of audio quality produced by the decoder at a BER= 10^{-3} would, except for very critical audio material, be sufficient in a moving vehicle because of the increase in ambient noise at high vehicle speed. Since the factor of 2 in maximum vehicular speed was found to apply between Modes II and 1.5, the results for Mode I were simply extrapolated by a factor of 2 from those obtained for Mode 1.5.

Hardware measurements

Measurements were conducted on actual 3rd–generation Eureka 147 hardware for Modes I and

II through a channel simulator (HP 11759C), to confirm the validity of the results. The results for two urban models are shown in *Fig. 3b*. Both models are based upon the COST 207 "typical urban" recommendation for 6–path UHF channel simulation. In one version, the first two paths are Rayleigh fading (classical U–shaped Doppler spectrum), whereas the remaining four have discrete Doppler components which approximate the Gaussian spectrum recommended in the TU model. In the second version, all six paths are Rayleigh faded with U–shaped Doppler spectrum, which produces very difficult reception conditions. This latter model is similar to the one used in the computer simulations. In both cases, and especially in the case of the fully Rayleigh case, the measured performance is somewhat worse than that predicted through simulation. Another effect also seems to appear in the case of Mode I which tends to make the measurement worse; that is the effect of the residual phase noise in the system which will tend to make the system fail at lower speed.

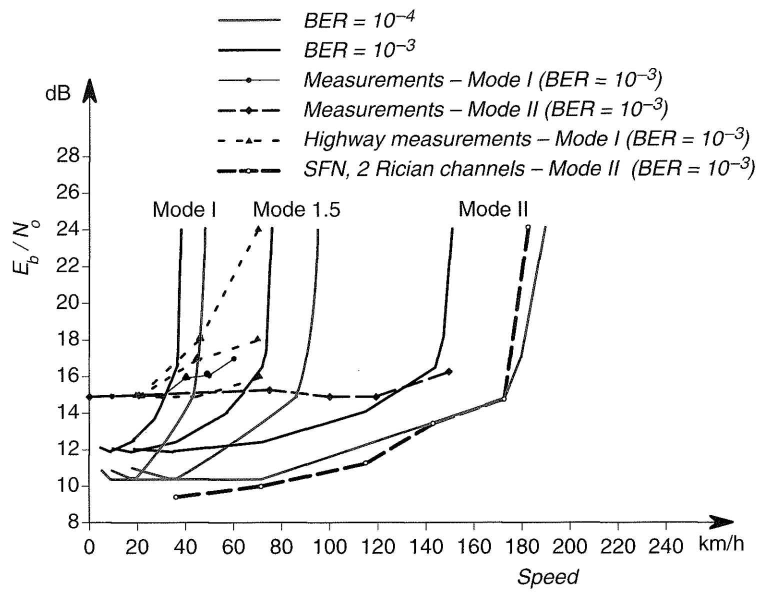
The results for the rural models are shown in *Fig. 4b*. One of the models is based upon the COST 207 "rural area" recommendation; it includes a first path with a Rician distribution, and the remaining paths are Rayleigh. The Rician *K*–factor for the case shown was about 2 dB. The other model is based upon a wideband channel measurement performed in a rural area near Trois–Rivières, Québec; in this case, all six paths were modelled as Rayleigh fading (U–shaped Doppler spectrum), producing a "worst–case" scenario. This latter model is similar to the one used in the computer simulations. This is confirmed by the close correspondence between the speeds for which the system fails completely in both simulated and measured cases for both Modes I and II. As expected, the failure mode measured in the case of the COST 207 model with the Rician component occurs at much higher speed. This Rician propagation model will be typical of most cases of reception conditions in rural environment, especially in the case of highway reception where local clutter is minimized.

Field measurements

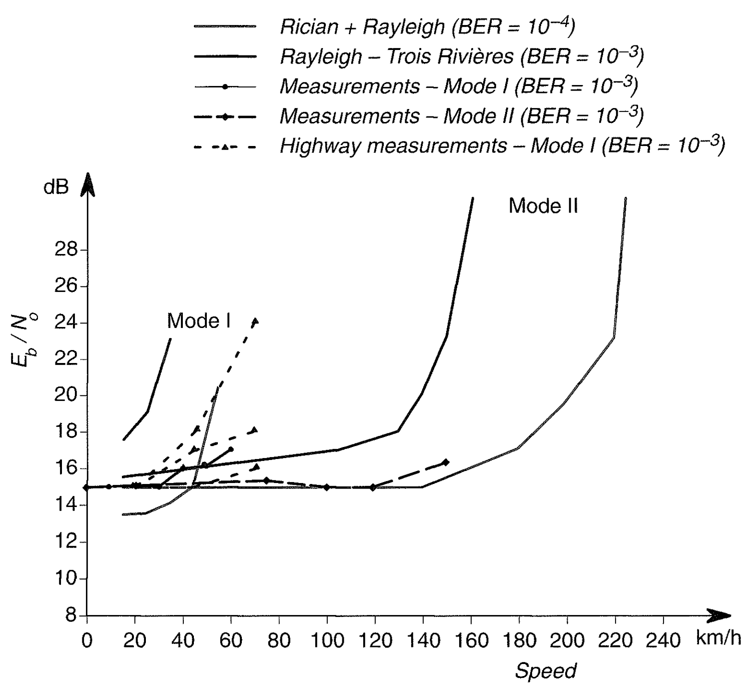
Results of actual field measurements conducted in the Montreal area are shown as dots on *Figs. 3* and *4*. The findings, from field measurements using the 3rd–generation hardware operating in Modes I and II, tend to indicate that, in the urban case, the results are very consistent with the results measured in laboratory, thus supporting the validity of the models used on the hardware simulator. The only clear difference is that the system seemed to need a minimum 15 dB of Eb/No to operate in the field, probably due to hardware implementation and possibly due to calibration error. What is important, however, is the shape of the curve and not its absolute position on the vertical axis. Again, the results for Mode I were found to be slightly more severe than expected, likely due to the effect of equipment phase noise that caused a reduction in the margin. Because of the excessive speeds required, only a few significant data points indicat-

Figure 4
Results of study of Doppler spread in a rural channel.

(a) Simulations and field measurements.



(b) Laboratory and field measurements.



ing the effect of Doppler spread could be obtained on highways with the system operating in Mode II. This showed in practice the comfortable headroom that Mode II offers at 1.5 GHz against Doppler spread.

In the rural case, the field results for Mode I operation indicate a better situation than predicted, even though the data points have a relatively large dispersion, indicating the variability of the phenomenon. Clearly, line of sight reception (Rician channel) is a major factor in rural coverage. The anticipated service deterioration at 1.5 GHz due to Doppler spread effects for Mode I was found to be not as severe as previously expected because most of the time, line of sight reception exists which reduces the effect of Doppler spread with the receiver tracking the Doppler shift of the main signal (Rician case). In fact, if the maximum speeds found for highway environments for Mode I were to be doubled to provide an estimate of the system performance for Mode 1.5, the maximum vehicle speed would be no less than 90 km/h.

The effect of reception in a SFN environment needs to be looked at carefully since a worse channel situation can be created by the presence on a number of active echoes of equivalent power, all being affected by different Doppler shifts caused by the vehicle displacement. In such a case, in the rural environment, a benign Rician channel can be translated into a more difficult Rayleigh channel due to the presence of these active echoes. The extent of locations where the reception of these active echoes at relatively equal power will occur is however somewhat limited. This has to be considered in establishing the probability of the service being affected by this phenomenon.

Discussion

Since the key element, in the context of the Doppler spread, is the speed of the vehicle, the level of audio quality produced by the decoder at BER= 10^{-3} is expected to be sufficient, except for the most critical audio material for a moving vehicle because of the increase in ambient noise at higher speed. The point of failure due to Doppler spread should therefore be considered for BER= 10^{-3}. It was found that Mode II gives a solid performance in all practical field situations. On the other hand, Mode I is clearly insufficient for operation at 1.5 GHz since the system fails at speeds as low as 40 km/h. However, the new Mode 1.5 would provide adequate service for most situations of moving vehicles (system breaking at 80–100 km/h in both urban and rural environments with no strong line–of–sight component), although not securing the solid headroom that is observed with Mode II. Because of the obvious speed limitation in obstructed urban areas and the likelihood of larger margin due to the probable presence of higher field–strengths close to transmitters, the urban case is not seen as constraining.

In the case of rural reception, it is expected that the channel type will be Rician in most of the cases, especially on highways where the vehicles can move at high speed since these highways are usually elevated relative to the surrounding terrain and have limited clutter in the immediate environment. The cases depicted in *Fig. 4a* for the rural channel are therefore clearly the worst case since they represent the fully obstructed Rayleigh channel with no direct path. In practice, it is expected that Mode 1.5 will allow vehicle speeds markedly higher on highways than shown in the Figure. In the case of reception in a SFN environment, the channel model for rural reception tends to become closer to a Rayleigh channel when a number of active echoes is received at equivalent power. This results in a more severe constraint on the allowable vehicle speed and corresponds closely to the obstructed Rayleigh case described above as can be seen on *Fig. 4a*. In such a case, the presence of a number of active echoes will tend to improve the reception quality except that at high vehicle speed, the reception will become impaired by the effect of the Rayleigh channel, thus reducing the improvement due to the network gain. The extent of the actual reduction of service availability in such a circumstance is hard to establish since it depends on a lot of statistical variables.

One element that should be considered in establishing this trade–off between the point of failure due to Doppler spread and the use of large geographical separations in a SFN is that the probability of failure due to Doppler spread is based on the joint probabilities of a vehicle travelling at high speed, moving through a difficult reception environment, and with signal reception near threshold. The conjunction of these three events makes it less probable and should be taken into consideration in selecting the mode of operation based on practical conditions. Allowing the use of this Mode 1.5 would give the broadcaster the possibility to verify the extent of failure in the case of high speed vehicles and use the best mode for the specific broadcasters' operation.

2.3.3. *Effect of carrier phase noise*

Concern had been raised that manufacturers may have difficulty meeting tighter tolerances especially on the receiver local oscillator if a longer symbol period at 1.5 GHz was employed. Some measurements were therefore made on actual 3rd–generation equipment and the results are presented in *Fig. 5*. It was found that the tolerances were not as tight as expected and in fact, the current prototype implementation of the 1.5 GHz RF front end meets the requirement even for Mode I. This explains why reliable measurements using Mode I could be done in the field with this equipment. It is therefore expected that the phase noise tolerance for a new Mode 1.5 would be currently achievable. Furthermore it is anticipated that volume production of receivers, capable of meeting the requirements to operate in Mode 1.5 at 1.5 GHz, will be technically feasible within five years. It is therefore concluded that this should not be a constraining factor in the decision to include a new Mode 1.5 in the emission standard.

2.3.4. Conclusion regarding mode

Considering the importance of being able to provide efficient and flexible large area SFN operation at 1.5 GHz, it is believed that operation with a larger guard interval than offered by Mode II (62.5 µs) would be advantageous. While Mode II was found to work well, through computer simulation, with wide transmitter separation in a SFN for smooth terrain environment, it is expected that specific engineering measures will be needed to operate with such large transmitter separations in a less uniform environment. The introduction of Mode 1.5 would greatly facilitate the implementation of SFN with large transmitter separations and thus would provide more flexibility in the localization of these transmitters.

2.4. Receiving antenna characteristics for mixed terrestrial/satellite sound broadcasting

A critical element in developing the mixed concept is a receiving antenna which allows reception from both terrestrial and satellite transmissions in the same frequency band. Results of early studies investigating the technical feasibility of such antennas are reported in this section.

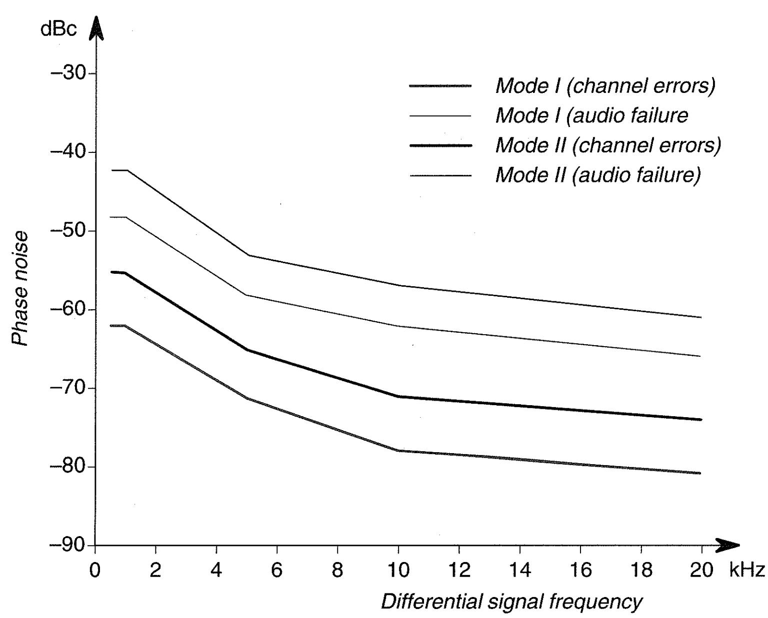
2.4.1. System assumptions

It is assumed that the polarization used for the satellite segment would be circular because polarization alignment at the receiver in the case of vehicular and portable reception would be difficult to maintain. Furthermore, Faraday rotation in the frequency range considered for the service is not negligible. At the receiving antenna, a trade–off exists between the polarization purity of a circularly polarized receiving antenna with inherent losses associated with increased complexity of the feed structure, and the use of a simpler linearly polarized antenna with the 3 dB loss from reception of only half the power. Improved frequency re–use based on orthogonal polarization is not anticipated for this service. In the case of the terrestrial segment, vertical polarization is assumed since vertical alignment can be maintained in most cases.

It is further assumed in this study that if a technology like Eureka 147 (i.e. that makes constructive use of the signal reflections) is used, there is no advantage in using a uni–directional receiving antenna, since the advantage of using reflections from various directions to sustain a proper received power would be lost.

Depending on the type of satellite orbit used for the service, the receiving antenna requirements could be somewhat different. In the case of geostationary satellites, the signal would be received at a specific elevation angle depending on the latitude and the longitude difference between the satellite at the receiving location. A fixed antenna which can be aimed at the satellite could be directional while a car antenna would have to be omnidirectional in the horizontal plane but could be optimized for maximum gain at the given elevation angle. In the case of a highly elliptical orbit (e.g. Molnya orbits) having its apogee at local zenith, the receiving antenna for vehicular application could be optimized for maximum gain towards the zenith.

Figure 5
Phase noise tolerance of 3rd–generation Eureka–147 DAB equipment.



2.4.2. *Types of antenna for mixed satellite/terrestrial service*

Receiving antennas should be able to receive from both satellite and terrestrial transmitters without need for physical reconfiguration. The antennas would need to be of relatively small size and minimum complexity for low cost implementation. The best radiation pattern for the receiving antenna in the context of a mixed service using a geostationary satellite would be a near–hemispherical pattern with a maximum gain at the mid–range of the elevation angle at which the satellite is received over the whole service area (e.g. 5 dBic (copolar gain relative to isotropic)) and still enough gain towards the horizontal direction to allow for terrestrial reception (e.g. 0 dBi). Three generic types of antennas could be used to allow reception of satellite and terrestrial transmissions in the same frequency band:

Fixed pattern

Antenna structure which provides adequate gain towards both satellite and terrestrial transmitters. Typically, such an antenna would be of tuned–wire structure or microstrip structure with complementary ground plane to produce a circularly–symmetrical pattern in the horizontal plane. Some implementations can give up to 6 dBic at a given elevation angle while still maintaining a 0 dBi gain in the horizontal direction.

Switchable pattern

Integrated double antenna structure which allows separate and better optimization of the satellite and terrestrial coverage. The antenna feed would be remotely switched with the channel selection on the receiver. Tuned–wire or microstrip structures could be used for the satellite reception and a 1/4 vertical monopole or 0–order mode microstrip patch would be used for terrestrial reception, both producing a circularly–symmetrical pattern in the horizontal plane. This could produce a gain of 5 dBic in the satellite direction while providing some 6 dBi in the horizontal plane.

Electronically–steerable pattern

More complex structures based on phased arrays providing higher on–axis gain (e.g. 15 dBic for 40 x 60 beamwidth) which could be steered automatically at satellite or terrestrial transmissions or even towards a predominant echo. The tracking system would automatically adjust for the mixed terrestrial/satellite service. The tracking system would need to maximize the amount of power present in the selected channel, thus the receiver IF section would need to be included in the optimization loop. These features would probably only be available on receivers in the higher price range. Also, the size of the active phased array is likely to be larger.

2.4.3. *Active antennas*

Passive antennas, either mast type (helix design) or low profile type (printed microstrip type) and in the case of phased arrays, all suffer the problem of bulkiness. Latest developments in active antennas show promises for a reduction in size through the use of integrated active amplifying and phase shifting elements. These active elements provide more flexibility in pattern shaping, size reduction (as much as 50%) and smaller substrate thickness. Although initially more complex, it is possible that through volume production, these techniques can be used even for consumer type receiving installations.

2.5. *Receiver front end for the mixed terrestrial/satellite concept*

The applicability of the mixed concept depends on, among other things, the feasibility of a receiver front end capable of receiving radio broadcasts from satellite, as well as from terrestrial transmitters. Research work was undertaken to first establish the receiver front end architecture and key components performance specifications such as compression point, dynamic range, selectivity, synthesizer frequency steps, etc. Then a computer simulation program was used to study the performance of the front end and to do parametric studies to further refine the design.

2.5.1. *Receiver front end architecture*

Several conflicting requirements must be addressed in the design of the receiver. First, the desire to have a front end filter which excludes all unwanted dominant signals in the neighbouring bands, but which passes all DRB signals, as the first element of the receiver must be considered in light of the equally important desire to establish a low noise figure by having a low noise amplifier as the first element after the antenna. Second, the desire to provide significant gain with the low noise amplifier must be considered in light of the high dynamic range requirement on all components preceding the DRB channel (1.5 MHz block) selection filter. Third, the desire to locate the DRB channel selection filter before down conversion (where it must be tunable, of high Q and subsequently lossy and costly) so unwanted RF signals are attenuated before exposure to the mixer, must be considered in light of its simplicity if located after the down conversion (where it is fixed in frequency, of low Q and loss), even though the mixer is now exposed to more saturation. Several scenarios were considered for the front end architecture and one was retained for further investigation. It interleaves low noise amplifiers and front end filters in order to suppress strong out–of–band interference, while establishing a good noise figure and avoiding compression before conversion. Given the relatively low gain of the first LNA (about 14 dB), a very high compression point is achieved thus allowing many strong terrestrial DRB adjacent channels with minimal effect on the weak satellite signal. Further, after down conversion, it interleaves amplifiers and DRB channel selection filters to suppress the strong adjacent channels. Then the AGC takes care of the large variations in signal strength with three cascaded variable gain amplifiers.

2.5.2. Computer simulations

The front end architecture described above was implemented in a specialised software program that allows a designer to evaluate the performance of an RF system based on the parameters of the individual circuit components. Tests include effects of cascaded gain, noise figure, 1dB compression point, filters, etc. Since wideband DRB signals could not be simulated with this software, CW signals were used instead. Results of these simulations show that in the case of CW on adjacent channels, signals can be treated adequately even in a situation where the receiver is tuned to a weak satellite channel adjacent to a strong terrestrial channel. A rejection of 116 dB is possible with a desired signal of –103 dBm, 1.538 MHz away from a –30 dBm unwanted signal. The simulated system has a dynamic range of 74 dB with a noise figure of 1.7 dB. This conclusion is only valid for CW signals.

3. Canadian field trials

3.1. Objectives of the DRB field trial projects

When starting up a broadcasting service which is based on a new encoding/modulation scheme, using a frequency band which is unfamiliar to broadcasters, new territory is being charted. It is therefore necessary to acquire empirical data to verify theoretical projections and suppositions. A primary objective of the DRB field trials is to put the proper programs or mechanisms into place to obtain the necessary support information.

In the technical area, in order to plan effectively, information is clearly needed on many aspects of propagation at L–band. We need to know how far L–band signals carry over a variety of terrain conditions, using various combinations of antenna height and power. The percentage of locations and time the signals are available at a receive antenna height of 1.5 m. are required in order to develop and verify an appropriate propagation model. The attenuating effect of various kinds of buildings and ground clutter including tree foliage are also essential elements in developing planning criteria for DRB. From an interference perspective, long–term propagation measurements (seasonal and daily variations) characteristics are needed to establish DRB interference criteria and coordination procedures with systems of the Fixed Service.

In addition to propagation factors, we need to demonstrate the feasibility and evaluate various transmitter network configurations such as single transmitter with on–channel coverage extenders and gap–fillers, limited and large–area SFNs, in order to ascertain optimum system parameters at L–band. Experience with L–band DRB receiving and transmission hardware (antennas, LNA, filters etc.) would be beneficial for evaluating the coverage/power/cost relationship.

In the non–technical area there is a need to familiarize the public, government and broadcasting industry in Canada with DRB in order to establish the overall objectives for the new service.

These objectives can best be met by carrying out programming trials, demonstrations and surveys, as well as digital audio networking and pre–operational experiments.

3.2. Coverage measurements at L–band

3.2.1. Ottawa and Montreal measurements

Propagation measurements were performed in Ottawa (Ontario) and Montreal (Quèbec) in the June–August 1991 time frame. An unmodulated carrier at 1497 MHz was transmitted at an effective radiated power (ERP) of 8 kW. The transmitting effective height above average terrain (EHAAT) was 61 meters in Ottawa and 230 meters in Montreal. The receiving antenna employed was an experimental omnidirectional 1.5 GHz vertical 1/4 monopole.

Before the tests, coverage predictions were made using VHF/UHF propagation software program (PREDICT) developed by the Communication

Research Centre (CRC). This software uses a combination of various propagation models and adjustment factors based on measurements, and can use terrain topography data including ground clutter. Measurement routes were selected in various environments (i.e dense urban, urban, suburban and rural areas) including potential trouble spots identified by PREDICT, suspected gaps, underpasses, tunnels as well as measurements at the predicted limit of coverage. In total 1680 eight–hundred meter sections consisting of close to 53 million measurement points were recorded and analyzed. In designing the test and analysis procedure, the expected performance of the most developed DRB system was considered (i.e. Eureka 147/DAB system).

The following observations were reached from these preliminary measurements:

- Generally, L–band propagation was found to be similar to propagation experience in the UHF television band. Measurements correlated favourably with the PREDICT software with respect to location of coverage gaps and identification of coverage limits, however there were insufficient data to determine whether PREDICT was capable of estimating coverage availability to the level and accuracy required for DRB planning.

- The most significant attenuation due to tree foliage occurred in areas near the transmitter where the signal strength was high. Reception under bridges, in underpasses and tunnels was not found to be more of a problem than experienced in the VHF/UHF bands;

- The received signal was found to be composed of two major components, a direct path signal including some strong reflected signals, and a low–power composite multipath (LPCM) signal (made up of the several low–level signals created by scattering and multiple reflections) arriving at the receive antenna from several directions within varying delays. Within the coverage area, the average level of the LPCM signal was often above the DRB receiver threshold, thus providing for service continuity even when the direct signal component was strongly attenuated or blocked. Because the LPCM is composed of signals from several directions, it is not affected nearly as much by major obstructions and tree foliage as is the case for the direct signal path;

- In Ottawa, a coverage radius of approximately 35–40 km was achieved, while in Montreal a range of 45–60 km was achieved at the higher EHAAT.

3.2.2. Barrie measurements

Additional coverage measurements were carried out in Barrie (Ontario) in late 1992/early 1993. The terrain surrounding the Barrie site was more irregular than average (h 80 m) and the site allowed the transmit antenna height to be varied. Field–strength measurements of the Barrie transmissions at different transmit heights and along radials with varied terrain topography were made and compared with predictions derived from the sophisticated PREDICT propagation model.

It was concluded that it is possible to provide coverage at L–band with high availability, to areas with a radius up to approximately 45 km, even under difficult terrain conditions, using a single transmitter with ERPs comparable to those used in the VHF band. For example, with an ERP of 6 kW at 230 meters above ground level, 90% coverage availability was achieved up to 50 km, while with an ERP of 17 kW at 97 meters, the coverage reached approximately 45 km.

3.2.3. Trois–Rivières measurements

In the summer/fall of 1993, another test transmission facility was established in Trois–Rivières, Quèbec to further study the propagation and coverage characteristics at L–band. The Trois–Rivières site allowed evaluations using different terrain conditions and transmitting heights. The measurement data gathered were added to the database made up of the 1991 Ottawa and Montreal L–band measurements as well as the 1992/93 Barrie tests. The Trois–Rivières trials included measurements up to 200 km from the transmitter as well as fixed reception sites to evaluate time and seasonal variability below and above the horizon in order to characterize interference at L–band. The results of these measurements will serve to refine the propagation model for terrestrial DRB at L–band.

In Trois–Rivières, ERPs of 13 and 42 kW were used with transmitting height of 100 and 200 meters, yielding estimated DRB coverage radii varying between 60 to 70 km.

3.2.4. Indoor reception measurements

Although penetration losses in building material are higher at L–band than at VHF, field measurements have shown that indoor reception at L–band may not be more of a problem than experienced by FM at VHF.

Indoor reception field strength measurements were carried out in the summer of 1991, in Montreal, in various buildings (office buildings, apartment buildings and ordinary houses) located between 0.5 to 20 km from the transmitter site. Types of construction included ferro–concrete with exterior surfacing made of bricks, concrete or aluminum, and also wood construction with aluminum facing. Indoor measurements were made on various floors (i.e top, middle, ground and basements), at various locations. For reference purposes, outdoor measurements where made at ground level, and where possible on the roof of buildings. The following conclusions were drawn:

- Building penetration losses ranged from 3–30 dB with typical losses in the 15–20 dB range.
- The penetration losses near windows was typically 8 dB.
- With the exception of two locations at the basement level, no location was found where the field strength was not at least 10 dB above the expected threshold of the DRB receiver.
- Several locations where FM reception was inadequate, presented a sufficient field strength for satisfactory DRB reception.

Indoor penetration is possible through windows, and once inside multipath propagation is very effective at L–band as indicated by the standing–wave fields measured inside. Hence, a system like DRB which makes constructive use of echos should work well in such an environment. Multiple transmitter coverage concepts would also improve indoor reception by increasing the number of signal entries in buildings.

3.3. System and network experimentation

3.3.1. Two–site facilities

In autumn 1992, a two–site DRB L–band test transmission facility was established in Toronto–Barrie (Ontario) to investigate the feasibility of using a synchronized SFN for large area coverage with transmitter spacing in the order of 80 km. This separation exceeds what would normally be considered permissible using Mode III considering the system's limited ability to cope with echoes with large delays. The tests were carried out with 2nd–generation Eureka 147 DRB hardware (with a 3.5 MHz RF bandwidth and a symbol guard interval of 32 µs, i.e. Mode III). With this hardware the size of the area where the signals from both Toronto and Barrie arrive within the guard interval and combine constructively was limited to approximately 12 km. By using digital delay, the guard interval was "centred" at the midpoint between both transmitters.

The results of the measurements were reported to the CCIR in January 1993, at NAB94 in Las Vegas and to the ITU/RS Working Party 10B meetings in October 1993. It was concluded from the measurements that, at least under some conditions, it is possible to space transmitters at distances up to 85 km in a synchronized SFN operating at L–band even with the guard interval area limited to 12 km. These preliminary tests indicated that further measurements were required to determine the feasibility of this concept for achieving high coverage availability with network configurations using more than two transmitters.

The transmitting parameters for Toronto were an ERP of 12 kW, 364 meters above ground level (CN Tower) while those for Barrie (located almost due North) were an ERP of 6 kW, 230 meters above ground level. Similarly to the results obtained in the December 1991 Toronto trials using a single transmitter with a lower ERP, the measured coverage around Toronto (northern arc) with the SFN, was continuous (close to 99% locations) up to approximately 40 km but extended farther in certain directions. It was generally terrain limited. Even in the densely–built high–rise city centre characterized by heavy shadowing and strong multipath, the reception was virtually perfect.

The measured coverage in the difficult terrain south of the Barrie transmitter was estimated to be good in 90% to 99% locations, with the exception of one area, and extended up to 50 km and more in some directions. Again, terrain seemed to be the limiting factor.

In some areas intermittent reception was found where received field strengths were below threshold due to terrain shadowing, and/or signals arrived outside the system guard interval. In most cases these outages could be resolved by employing one or more of the following measures:

- Use of transmitting space diversity which could be provided by adjacent transmitters located to the East and West, configured as a wide area multi–transmitter SFN.
- Use of a longer guard interval longer than that of Mode III.
- Increased ERP or antenna height at Barrie or Toronto.
- Use of gap–fillers in affected areas.

It was concluded also that the majority of reception problems due specifically to out–of–guard interval

Parameter	Mount Royal	Rigaud	Lac Echo
Coordinates long (deg, min, sec) lat	73°35'32" 45°30'20"	74°17'42" 45°27'04"	74°01'20" 45°51'48"
Transmit frequency (vertical polarization) (MHz)	1468.75	1468.75	1468.75
Ground height a.s.l. (m)	226	220	292
Antenna height a.g.l. (m)	30	30	70
Antenna beamwidth horizontal (E plane) (deg.) vertical (H plane) (deg.)	360 4	360 4	120 4
Beam tilt (deg.)	1.5	1.5	4
Antenna type (Tiltek)	omni	omni	cardioid
Antenna gain (dBd)	10.9	10.9	15.9
Transmitter manufacturer	Locus	Locus	Thomcast
Transmitter output power (W)	170	17	22.5
Transmission line loss (dB)	0.8	1.0	1.8
ERP (W)	1500	130	42

Table 1
Characteristics of the stations in the SFN.

interference could be corrected with a larger guard interval (like Mode II or longer). Also, in some instances reception could be improved by using a better synchronization strategy in the DRB receiver.

3.3.2. Three–site facility

In January 1994, a three–site DRB experimental network was established in the Montreal region. The facility consists of three transmitting installations established at existing radiocommunication sites on Mount–Royal in Montreal, in Rigaud and Lac Echo, Quèbec. The three sites form an approximate equilateral triangle with transmitter spacing of 53 km.

In line with the Canadian DRB service objectives, the facilities were designed to cover, in part, approximately the same area as existing high–power FM radio stations in Montreal. The transmitter spacing of 53 km was chosen because it is considered to be representative of future DRB networks. DRB coverage trials in the VHF and UHF range have shown that, in general, it will be difficult to achieve 90% to 99% service availability with transmitter spacing greater than 50–60 km.

The station parameters in the SFN configuration are shown in *Table 1*.

The DRB equipment utilized is 3rd–generation Eureka 147/DAB hardware. The trials are being carried out using principally Mode II parameters, although Mode III is also being experimented with. The three SFN co–channel transmitters are fed by a secondary distribution network with the signals delayed appropriately so that all transmitters are broadcasting the same signal in time synchronism.

The three–site facility is convertible from a synchronized SFN to a coverage extension network. Tests will be performed using both configurations. In the coverage extension trials, the Rigaud and Lac Echo transmitters will be fed off–air from the Mount–Royal station and will be rebroadcasting the signal on the same frequency. The transmitting antennas at Rigaud and Lac Echo will be changed to directional type and re–oriented away from the main transmitter. Highly directional receiving antennas will also be installed at these sites.

Using both the SFN and the coverage extension configurations will allow:

- the coverage extension to the west to approximate that available from a large FM station and permit a comparison between L–band DRB and VHF/FM coverage and cost;
- coverage overlap of the three transmitters to achieve 90% to 99% availability and permit evaluation of the effectiveness of using co–channel transmitting space diversity;
- appropriate transmitter spacing to evaluate guard interval constraints (i.e. 64 μs (Mode II) and 32 μs (Mode III) with Eureka 147 3rd–generation DRB equipment);
- the opportunity to evaluate and compare existing FM technology with the hardware and the economics of using L–band for DRB. Also, it allows evaluation of the merits of using coverage extenders in lieu of SFNs for achieving coverage.

In addition, as part of the project, monitoring stations were established in strategic locations in order to monitor and periodically verify the performance of the three–site SFN, as well as to measure the short and long term fading of the DRB signal at various distances; inside the coverage area, at the edge of coverage area and over the horizon. The latter data will help to establish intra–service interference criteria (i.e. frequency re–use separation distances) and coordination procedures with systems of the Fixed Service. With the addition of two other DRB transmitters to the three–transmitter SFN, in the west and in the north–east, it would be possible to duplicate completely the coverage of the existing high–power FM radio station. A direct comparison could then be made between a five–site DRB SFN facility transmitting 5 to 6 stereophonic CD–quality programmes with a service availability of 90 to 99% using ERPs in the 5 kW range, versus a 100 kW single–site FM transmitter broadcasting only one stereo programme with a FM radio audio quality and an availability of (50%, 50%).

Measurements to study and document the operation and performance of the two network configurations are being carried out. The area around and between the three transmitters is surveyed and receiver sound decoding is monitored together with received power, bit–error rate, channel impulse response and field strength.

The measurement programme is planned in four phases:

1) SFN testing and optimization;
2) synchronized SFN experimentation and performance assessment;
3) coverage extension, coverage shaping and gap–filling experimentation;
4) multiple frequency network experimentation.

In the first phase of the measurement programme, relative delays, vertical beam tilt and ERPs have been optimized to maximize the overall coverage and minimize the gaps caused by terrain shadowing and by inter–transmitter interference due to signals arriving outside the guard interval of the system.

In the second phase, the objective is to delineate the coverage obtained with the SFN and identify as well as attempt to relate the coverage gaps to received power, channel impulse response, and other factors affecting the bit–error rate such as phase noise, intermodulation, interference, etc. Several elements contribute to decrease the C/N+I below the receiver threshold, and their interaction needs to be studied.

In the third phase, the SFN links are disconnected and the concept of on–channel re–transmitters serving as coverage extenders/shapers or gap–fillers is studied. Measurements to evaluate the extent to which this concept can be used are performed.

At the time of writing this article, the project was only in the second phase and the results on the performance of the SFN, currently being prepared, are very encouraging particularly with respect to conformity with predicted coverage.

It is expected that the forthcoming measurements will show how the various transmitter network architectures for terrestrial DRB in the 1452 –1492 MHz range can be used to meet the Canadian DRB service and coverage requirements.

4. Planning for DRB implementation in canada

The ultimate goal is to implement a domestic mixed satellite/terrestrial DRB service for Canada which will meet a number of objectives. The major objectives for the new service, many of which were delineated by the Task Force on the introduction of Digital Radio as guiding principles, are described in *Section 1.3.*

Prior to implementing the service it is necessary to develop a national allotment plan to provide an orderly implementation which will meet these objectives to the extent that spectrum permits. The terrestrial DRB allotment plan will contain as a minimum a list of the DRB networks specifying for each network:

- The DRB service area defining the licensed coverage area for the DRB network.
- The listing of the AM and FM stations assigned to each DRB service area or network (i.e. station grouping). This will include a merit factor indicating how well the DRB network duplicates each of the AM and FM station coverages forming the group.
- Frequency reuse contour for DRB network. This contour indicates the minimum distance that another co–channel DRB service area can be located without resulting in unacceptable interference.
- A frequency assignment to each DRB network taking into account a future satellite component and minimizing the impact on existing fixed systems operating within the band.

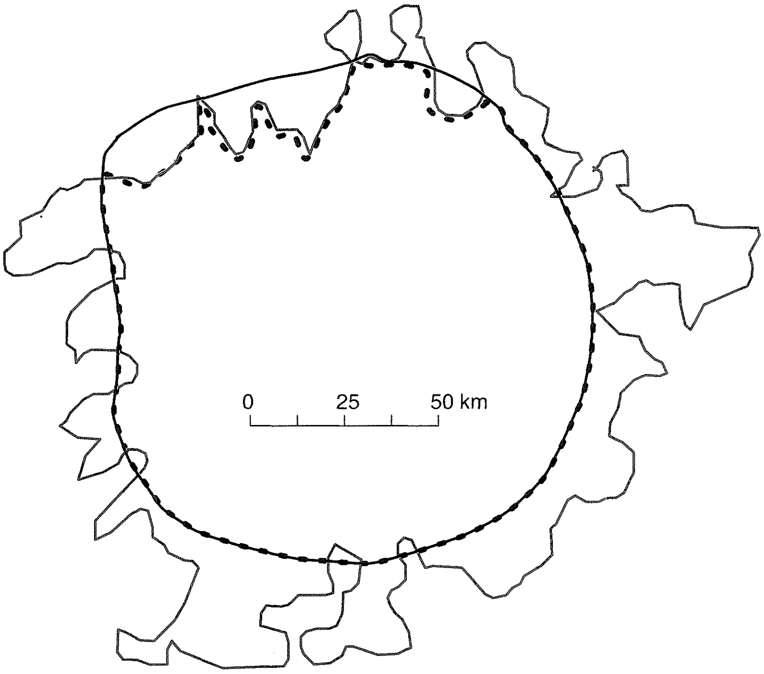
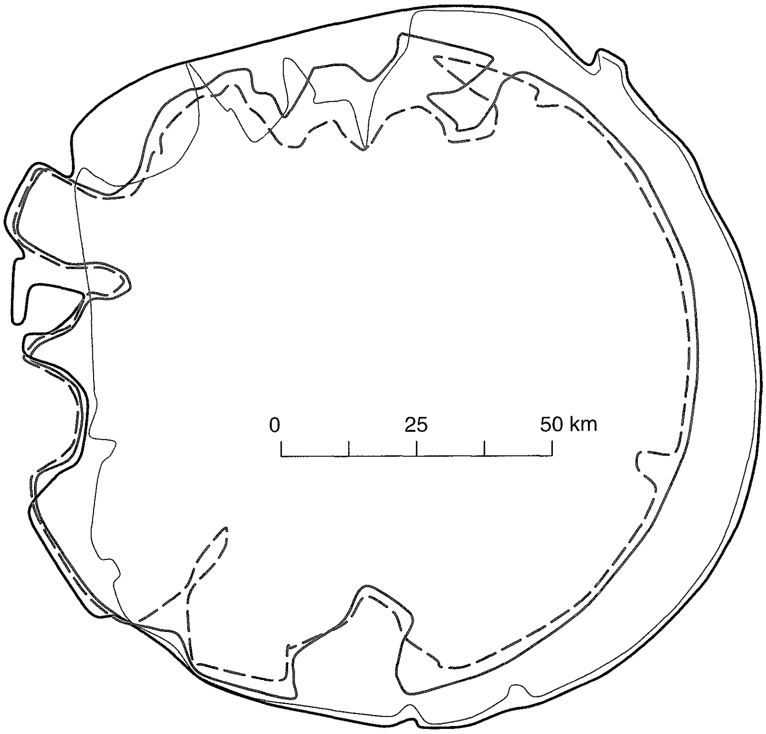


Figure 6
Generation of the FR(50,50) contour.

Station F(50,50) contour
Station predicted contour – R(50,50)
Station FR(50,50) contour

Figure 7
Example of station grouping.

DRB service area
FM station A
FM station B
FM station C
FR(50,50) contours



There are three distinct steps that can be identified in development of a terrestrial DRB (T–DRB) allotment plan. These are:

- Grouping of stations and identification of coverage requirements.
- Identification of key DRB network parameters that impact on the spectrum usage and system implementation.
- Prioritizing and assigning frequencies to the networks.

These steps are discussed in the following sections.

4.1. DRB coverage planning

Terrestrial DRB in Canada is being planned as a replacement for the AM and FM radio services. Hence important objectives that have been identified in developing an allotment plan are that it be capable of providing existing AM and FM stations with a DRB channel and that the DRB coverage area duplicate as closely as possible the defined coverage area of the analogue service it is intended to replace. The difficulty in fully meeting this duplication objective results from the need to group a number of analogue stations to form a single DRB station or network in order to obtain good spectrum efficiency and minimize the cost of DRB implementation. Planning is based on the assumption that up to five analogue stations can be accommodated within one DRB station or network. This consideration, coupled with the large variance in the size and shape of AM and FM coverage areas serving a given region or market area, makes grouping of stations that achieves both good spectrum efficiency and coverage duplication very difficult.

The Task Force on the introduction of Digital Radio established a set of guiding principles for developing DRB service areas for FM and AM replacement. In summary these principles state that DRB coverage planning for AM and FM stations should be based on permitting:

- The replacement of the largest coverage FM station serving the community or market area. DRB coverage replacement of wide area AM stations serving the same area would be restricted initially to the equivalent to the highest class or equivalently, largest coverage FM station serving the area.
- Smaller coverage AM and FM stations within the area to retain their present coverage area with the potential to expand to the largest cover-

age defined for the area (i.e. highest class FM station).

- Possible future extension of the DRB coverage to include service to audiences that exist beyond the protected contour in the case of FM stations, or beyond the protected contour of the highest class FM station for the case of AM stations.

Fig. 6 illustrates the procedure used for defining the realistic coverage area for FM stations. The solid red contour depicts the licensed coverage contour for the station which is defined as the 500 μV/m field–strength contour as defined by the F(50,50) propagation curves (i.e. field–strength exceeded for 50% of locations and 50% of the time). The solid blue contour denotes the realistic 500 μV/m contour for 50% of locations and 50% of the time, denoted as R(50,50). The R(50,50) contour is derived using the computerized propagation model PREDICT as defined earlier. PREDICT uses the actual station emission parameters as well as detailed terrain elevation data including ground clutter in determining the realistic service contour, hence in very irregular terrain the R(50,50) contour can differ considerably from the station's licensed F(50,50) as illustrated in *Fig. 6.* Finally, the black herring bone contour defines the realistic coverage contour, FR(50,50), for the FM station which the DRB service area attempts to duplicate. The FR(50,50) contour is simply the common area defined by the licensed coverage contour, F(50,50) and the realistic contour, R(50,50).

For the AM case the station coverage to be duplicated is normally based on the 500 μV/m daytime contour but limited to the largest FM station serving the same market, which ever is the smallest. The latter condition is very critical as the daytime 500 μV/m contour of high–power (Class A) AM stations can greatly exceed the largest FM coverage.

The grouping of stations to form a DRB service area consists of combining up to five FM station FR(50,50) and AM station coverage serving a common area in a manner that maximizes duplication of coverage. The coverage duplication is measured by a merit factor for each analogue station forming the group. The area and population merit factors indicate how well the DRB service area duplicates each station forming the group in area and audience covered respectively. A merit factor of "one" indicates 100% duplication. The objective in grouping stations is to maximize the number of stations forming a DRB service area to provide spectrum efficiency and minimize implementation costs to each broadcaster while achieving good duplication of coverage (i.e. high merit factor). *Fig. 7* shows an example of grouping of three FM stations that have similar FR(50,50) coverage to form a DRB service area. The DRB service area, denoted by the herring bone contour, is the envelope formed by the envelope of the three station FR(50,50) coverage contours.

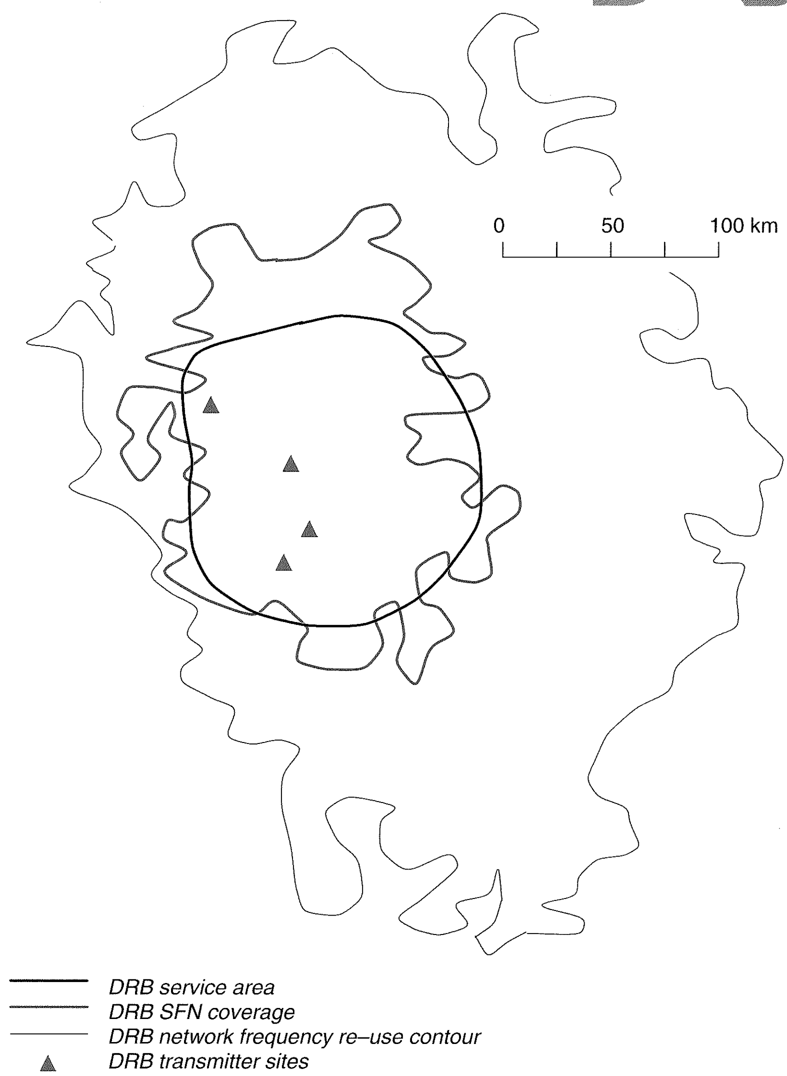


Figure 8
Example synthesis of DRB coverage.

4.2. DRB network synthesis and determination of frequency reuse contour

Once the DRB service areas are defined, the next step consists of synthesizing a DRB network at L–band to provide the realistic coverage of the DRB service area. A software program DRBPLAN-COV, discussed in *Section 4.5.*, is used to generate the network coverage. The software utilizes the PREDICT propagation model and terrain elevation data and simulates the DAB (COFDM) system to generate realistic coverage comprising single transmitters, augmented by gap fillers and

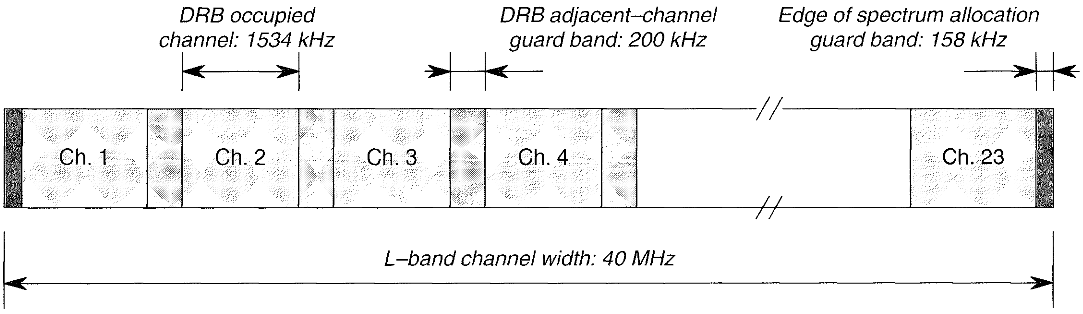
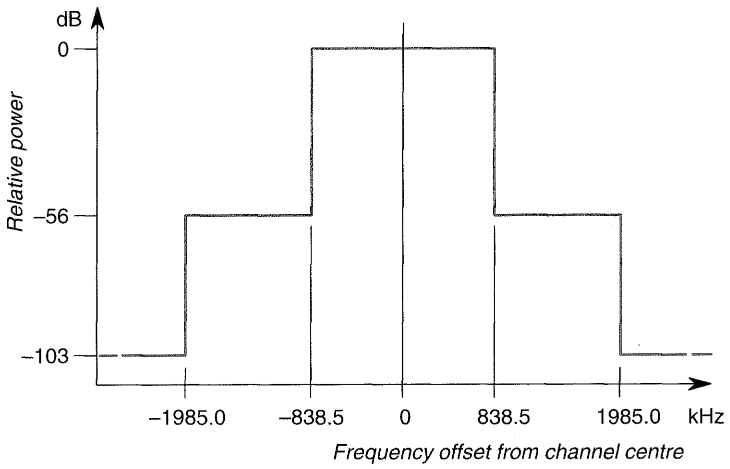


Figure 9
L–band DRB channel plan.

coverage extenders as required or SFNs depending on the size of the service area. Networks are designed to achieve 90% location and time coverage, defined as DR(90,90) coverage. Once the network parameters are determined the frequency reuse contour for the network is generated using DRBPLANCOV. The frequency reuse contour determines the separation required between co–channel DRB networks to meet the inter–network interference allowance set to 1 dB degradation in the network (E_b/N_o) for 90% or better of locations and time. The frequency reuse contour will be specified in the allotment plan for each DRB service area as this defines the inter–network interference constraints. Broadcasters can use various approaches to synthesize the DRB network coverage however the resultant frequency reuse contour must fall within the one specified in the allotment plan to insure that the interference criteria between networks will be met. *Fig. 8* illustrates the synthesis of a DRB network for the DRB service area defined in *Fig. 7* shown as the dashed blue contour. The solid blue contour shows the DR(90,90) coverage (i.e. DRB coverage to 90% of locations and 90% of time) of the four site SFN synthesized to duplicate the DRB service area. The dotted red contour represents the frequency reuse contour for the network. It represents the separation required to another co–channel DRB coverage area so that the degradation due to interference from this example network does not exceed 1 dB for 90% of locations and time.

Figure 10
L–band emission mask.



4.3. Frequency assignments and prioritization

The final stage in the allotment planning process is to assign frequencies (i.e. DRB channels) to the DRB networks. Assuming a DRB system having the characteristics of the Eureka 147 system, a draft channelization plan was developed as shown in *Fig. 9*. This channelization plan accommodates 23 DRB channels within the 40 MHz of L–band spectrum. Assignment of DRB channels to the DRB service areas are made according to established priorities and spectrum constraints such as:

- frequency reuse contours for the DRB service areas as defined in *Section 4.2.*;
- allowance for a future satellite DRB component in accordance with a mixed satellite/terrestrial DRB implementation;
- minimizing the impact on existing fixed services using the band.

Also, in congested areas where spectrum shortage exists, the Task Force on Digital Radio Implementation has established prioritization guidelines for assigning DRB channels between existing terrestrial services, unused terrestrial allotments, satellite DRB, future growth, etc..

In order to implement a future satellite DRB component to provide regional and national DRB programming services it is necessary to reserve satellite DRB channels when the terrestrial allotment plan is being prepared. Since the amount of interference into terrestrial DRB assignments from satellite DRB assignments depends on the separation between the satellite and terrestrial co–channel service areas, the DRB channels assigned to the satellite service will not be available for terrestrial use in certain geographical areas of the country. For example, the criteria used to establish the priorities for terrestrial channel assignments are:

1st priority
Channels not used by the satellite service.

2nd priority
Channels reserved for satellite that will result in 3 dB or less interference degradation to the terrestrial service.

3rd priority
Channels reserved for satellite usage if the terrestrial service area is outside the satellite beam footprint.

In the initial planning process an attempt is being made to allow for the assignment of two DRB channels per satellite beam on the basis described above.

In Canada the 1452–1492 MHz band is used by the Fixed Service to provide point–to–point and point–to–multipoint (P–MP) subscriber radio services. When assigning frequencies to DRB service areas it is important to take into account to the extent possible, existing fixed systems that may be interfered with or which could cause interference into the DRB service. A fixed service is considered affected if the aggregate interference (in the case of multiple transmitters in a DRB network) reduces the path fade margin by more than 1 dB (i.e. I/N –6 dB). Likewise a DRB service area is considered affected if the (I/N) –6 dB for 10% of locations and 10% of the time. *Fig. 10* shows the RF emission mask assumed for estimating the DRB interference into fixed system receivers. It is based on preliminary information contained in the draft handbook on DRB. Actual fixed system parameters are used in determining the level of interference and the path losses are based on PREDICT propagation program using actual terrain elevation data. When assigning frequencies to DRB service areas those frequencies that could cause interference to/from fixed systems will be identified and avoided if possible. If sufficient interference–free DRB frequencies are not available in locations where several channels are allotted, those channels which cause or result in least interference will be implemented first. The fact that most P–MP systems are located in rural and remote areas while terrestrial DRB systems are expected to be implemented initially within and near cities will probably allow many of the existing fixed systems to continue using their current frequencies for some time, perhaps indefinitely.

4.4. DRB planning software

As the development of a DRB allotment plan entails intensive computations and manipulation of large data bases, a DRB software package, referred to as "DRBPLN", along with multi–tasking work stations has been developed, to form a Digital Radio Planning System (DRPS). *Fig. 11* shows the architecture of DRPS including the major software modules, databases and interfaces. The system was developed on the basis of extensive application of graphical user interfaces (GUIs) permitting a high degree of user inter–action in carrying out the various steps in the allotment planning process.

DRBPLN is being developed to run on a 586–Pentium platform under the OS/2 operating system. This will provide the needed flexibility of multi–tasking of applications and distributed multi–processing to load–share the computation–intensive elements of DRBPLN among multiple Pentiums, inter–connected by a LAN.

4.4.1. Major DRBPLN modules

DRBPLN
This module performs the synthesis of DRB networks. The output consists of the realistic network coverage, network parameters such as transmitter locations, antenna characteristics and transmitter ERP. It also determines the frequency re–use contour for the network. It consists of the integration of parts of CRCCOV, PREDICT, CONVERT and user planning enhancements. The key element of this module is CRCCOV, a software package developed at the Communications Research Centre. CRCCOV synthesises DRB coverage by simulating the DAB system, taking into account active echoes from multiple transmitters in accordance to the DRB system operational characteristics.

MAPINFO (Windows version)
This is a commercial software package which allows the graphical display and analysis of geo–coded data bases. This is the main module used for displaying AM and FM coverage, determining coverage statistics, grouping of AM and FM stations to form DRB service areas, and assigning frequencies to DRB networks.

PREDICT
This is the propagation prediction module developed by the Communications Research Centre used in the determination of realistic FM coverage contours, DRB network synthesis (using CRCCOV), DRB network frequency re–use contours and to evaluate the impact on fixed systems. It predicts path losses based on 500m or DTED terrain elevation data. The model estimates signal strength over an area with percent location and time as input parameters.

4.4.2. DRBPLN databases

As shown in *Fig. 11,* DRBPLAN includes a number of data bases required in the development of the plan. These are:

500m and *DTED*
500 metre and 100 metre resolution terrain elevation data, respectively, including ground clutter information for most of Canada.

TWRS
Data base containing information on all registered communication and broadcasting towers in Canada.

AM/FM
Database containing essential parameters of Canadian AM and FM broadcast stations including the geo–coded contours of their licensed [F(50,50)] and realistic [R(50,50)] contours.

DRB_CELL
Database containing the essential parameters and contours, defining the DRB networks.

DRB_COV
File, containing the parameters and service contours of the DRB service areas.

DRB_PROT
Contains the parameters and contours of the frequency re–use contours.

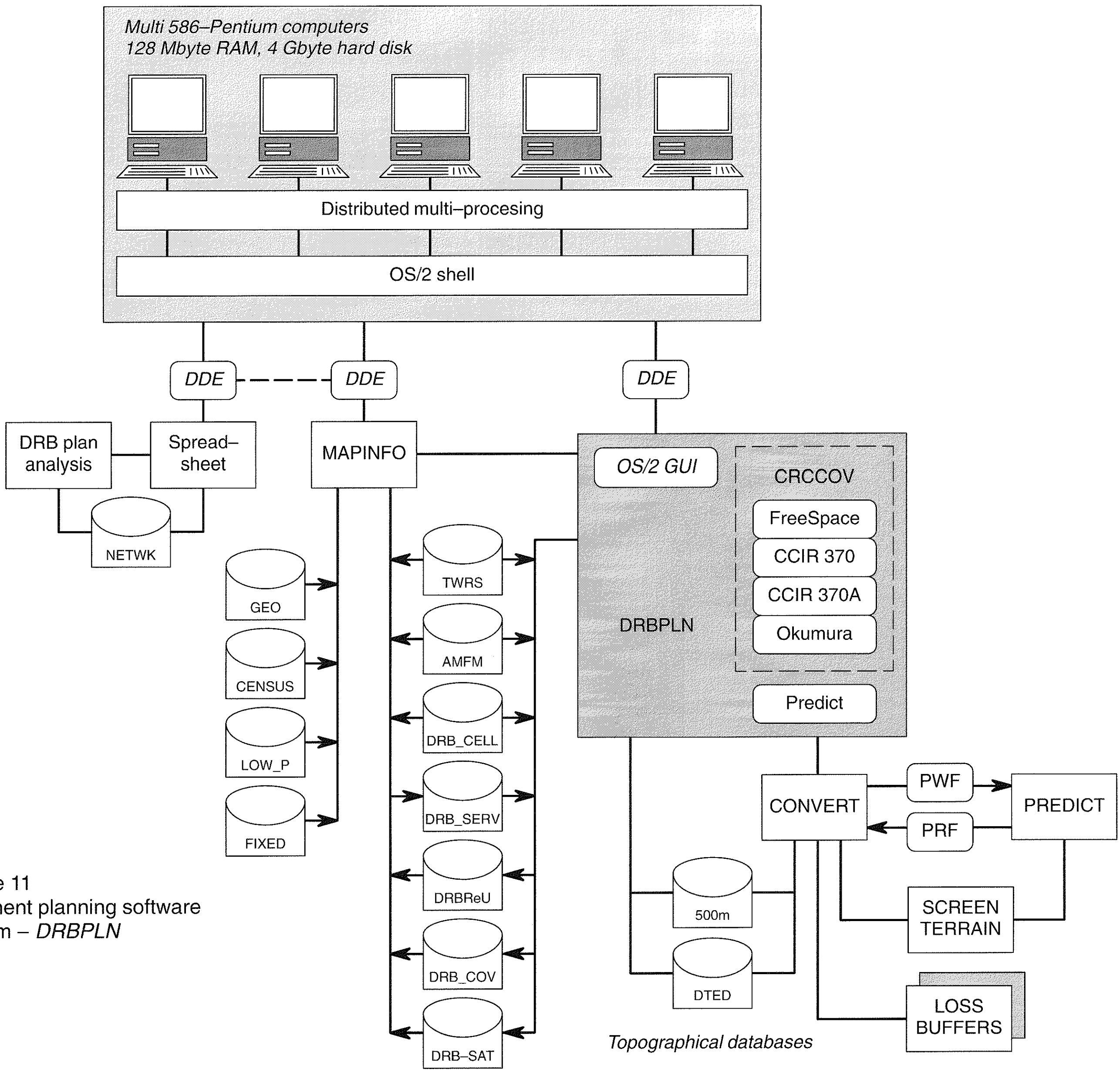


Figure 11
Allotment planning software system – *DRBPLN*

DRB_SERV
Contains the polygons defining the DRB service areas.

GEO
Database of Canadian geographical information including, cities, towns, highways, etc.

CENSUS
Data base containing the 1991 Canadian population census in geo–coded format.

NETWK
Database containing the DRB network including the frequency assignments.

FIXED
Database containing all relevant parameters of fixed stations currently operating within the 1452–1492 MHz band.

DRBSAT
This database contains the beam parameters and associated frequency assignments of the DRB satellite system.

5. Future work

Now that many of the technical and spectrum questions appear to be on their way to being settled, attention will be directing to other related issues, such as:

- Planning the roll–out of the new service. This will include working with Industry Canada to develop a practical domestic allotment plan, as well with the consumer equipment manufacturers to ensure that affordable receivers will follow quickly once the DRB service begins.
- Developing cost models to allow broadcasters to estimate the conversion costs;
- Determining suitable ownership models. Discussions will occur with the regulators to determine acceptable models for licensing and ownership of the multi–program transmitters that are an integral part of DRB.
- Promoting auxiliary data services. Broadcasters will need to promote and sell their spare data capacity, as a means of providing needed revenue during the early days of DRB, when receiver ownership by the general public is still low.

With respect to receiver front end architecture suitable for the mixed concept, research work so far has been encouraging. Further work is needed to test with COFDM signals and to produce prototypes at reasonable cost and size in order to make it a consumer product.

In the area of field trials, further studies are required with respect to the following:

- optimization of transmitting ERP/antenna height and locations within which the guard interval reinforces desired signals according terrain topography;
- optimization and design of transmitting antenna vertical pattern and tilt;
- optimization of the DRB receiver synchronization strategies;
- L–band DRB receiver antenna and RF front–end design (see *Section 2.4.1.*);
- distribution of programmes to SFN cells;
- operation in a mixed terrestrial/satellite DRB configuration including the hybrid satellite concept.

6. Conclusions

All of the above studies will be done in a partnership relationship that involves federal and provincial authorities, the regulators, and all broadcasters, including campus and community stations.

Since 1990, the many DRB projects in Canada have been a textbook case of cooperation among these players. The experience has clearly demonstrated how much can be accomplished when all interested parties work together to achieve a common goal.

Clearly, there is much left to be done. It will be many years before the transition from analogue to digital radio is complete in Canada. The speed of transition will largely be determined by the receiver manufacturers. Nevertheless, the broadcasters believe that the radio industry must move into the new digital era as quickly as possible, in order to survive in an increasingly competitive environment. Broadcasters must use this new technology not only to provide a better version of their current services, but also to develop new business opportunities.