Perth, 33°:	1% locations	5% locations	10% locations
Urban	20	12	7
Suburban	12	5	3
Rural, flat	11	4	2
Rural, forest	15	12	9
Open	2	2	<2
High-rise	>21	20	18
Dense urban	>21	18	16

Canberra, 51°	1% locations	5% locations	10% locations
Urban/Dense suburban	11	7	4
Suburban	8	3	2
Rural, flat	<5	<2	<2
Rural, forest	11	6	4
Open	2	<2	<2
High-rise	>21	12	4
Dense urban	20	6	3

Table 4.1: Signal fade depths (dB) as a function of the type of environment and elevation angle (light fading indicates values greater than 5 dB)

For these kinds of considerations (i.e. blockage, elevation angle, environment type), the carrier **frequency** has a relativity minor impact on the actual depth of fade (see Section 4.3.2.2). However, in the unlikely case of a satellite system that would have enough fade margin (i.e., 15 dB) to partially compensate signal blockage, the signal **bandwidth** would then become a factor, particularly in areas where multipath components are nearly as strong as the direct signal (if any). This situation is found in some parts of the urban and suburban areas where large buildings create reflections that are picked up by the omnidirectional receive antenna and make the main signal collapse each time they are out of phase. The magnitude of the fades due to multipath can be reduced by increasing the signal bandwidth. Flat fading progressively turns into selective fading while the bandwidth of the channel increases. In such cases, only selected portions of the bandwidth will collapse while the others will be strengthened by the presence of the multipath energy, making it recoverable. More discussions on the various fading modes can be found in Section 4.5.

Another important factor that must be considered when designing a service to mobile receivers is the **Doppler** effect. This manifests itself as an apparent shift (or spreading, in the case of multipath) of the transmit frequency as seen by the receiver in motion. The shift increases linearly with the speed of the vehicle and with the carrier frequency.

When there is a single main signal component received, the shift is easily tracked by the receiver AFC and the reception is not affected. When significant multipath is present , the various signal components can be shifted in frequency, in opposite directions, and result in "Doppler spreading". This condition is characterized by an arbitrary displacement (or spreading) in frequency of the signal components for which the receiver AFC cannot do much. This will be studied more thoroughly in Section 4.5.

4.4.2 Simplified channel models

Two channel models are often used to describe typical satellite and terrestrial broadcasting channels. Since they will often be referred to in this report, a definition is provided here:

Rician channel: One dominant incoming wave (line-of-sight or a strong reflection) accompanied by some weaker multipath components. A typical example is a terrestrial radio reception on a rural road. This model is also widely accepted as representative of satellite reception.

Rayleigh channel: Several multipath components of approximately equal amplitude, no dominant component because there is no consistent line-of-sight reception. Typical example: radio reception in a dense urban environment.

It is now possible to examine the channel conditions prevailing in various **types of environments**. To simplify the discussion, only three types of environments will be examined: the **urban** area, the **suburban** area and the **open rural** area.

Let's assume a single-carrier-per-channel (SCPC) satellite service received by a vehicle going from a rural community towards the downtown area of a large city. In the rural area, the impulse response of the channel can be depicted by a single pulse whose amplitude fluctuates from a maximum level (line-of-sight) to practically zero when some obstruction is encountered along the road. The antenna has some gain towards the satellite and reduced gain toward horizon resulting in a reduction of the multipath components from nearby reflecting surfaces. Since the vehicle is moving, the received signal frequency appears to be higher (or lower, depending on the direction of the vehicle relative to the satellite) than that transmitted by the satellite, due to the Doppler shift described above. In this case, since the signal will be received at a given elevation angle from the satellite, the Doppler shift will appear reduced by a factor of (cos θ). At very low elevation angles, the Doppler shift would be very similar to the terrestrial case whereas for a satellite at Zenith, there would not be any Doppler shift (cos 90° = 0)

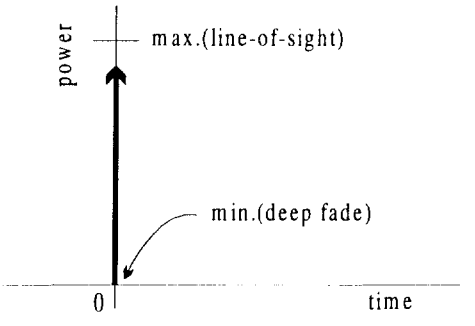

Figure 4.1: Simplified impulse response of a rural open channel.

As the vehicle approaches the more densely built-up area, fade occurrences on the direct path and their duration increase. The service availability begins to decrease and the service interruptions become noticeable. The channel impulse response consists in a large pulse representing the signal received from the satellite followed by a trail of progressively smaller pulses which represent the reflected signals from nearby surfaces, arriving shortly after the main signal, but with much less strength. As the vehicle approaches the city environment, the number, the depth and the duration of the fades on the main pulse will increase due to increased blockage whereas the number and the size of the following smaller pulses will increase due to the number of reflecting surfaces in the neighborhood (see Figure 4.2).

In the case where the satellite transmission only allows for a small fade margin, these later reflections will be lost in the thermal noise of the receiver and will be a negligible cause in the system failure (the main cause being the fading of the line-of-sight satellite signal). However, if the link margin is

large enough, these reflections will start to create fading (which may be flat or frequency selective, depending upon the signal bandwidth and the excess delay of the echoes) since the noise floor of the receiver will be comparatively lower. In general, in order to keep the required satellite power within a reasonable limit, the first case described above is a more reasonable assumption.

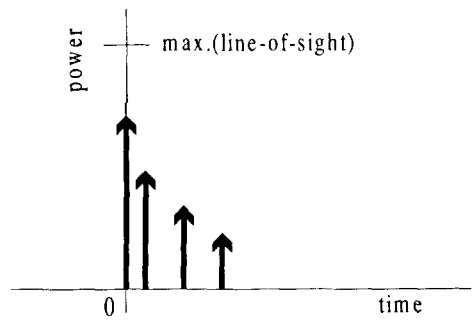

Figure 4.2: Simplified impulse response of a suburban channel.

Now let's assume that the receiver has reached the downtown area. Line-of-sight reception will be feasible at a reduced percentage of locations such as intersections, parking areas and streets parallel to the satellite's azimuth. Blockage from buildings will cause deep fades and the reflected signals will usually be too weak or too unstable to be of any use. The vehicle speed will be variable and, at times, very slow resulting in relatively long fades, rendering time-interleaving in the modulation less effective.

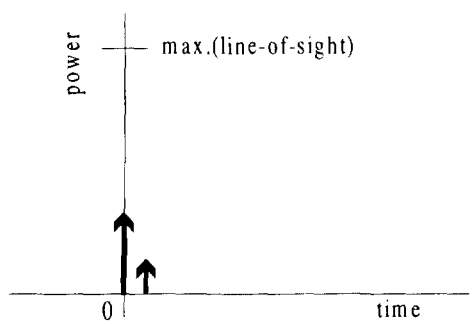

Figure 4.3: Simplified impulse response of an urban channel.

4.4.3 The need for gap-fillers

Our investigation so far has shown that limitations in satellite power will cause service interruptions in certain areas within the service contours. This is the case for areas where constant blockage is present due to terrain features, trees, buildings and other man-made structures. Due to the frequencies considered, the extra power required at the satellite to provide the required fade margin would be beyond practical limits. This is why another means has to be found to cover these shadowed areas. The deployment of on-channel terrestrial repeaters is considered to be the only effective way to provide **seamless coverage** for vehicular reception. This is the only way to locally supplement,with extra power, the satellite coverage in those areas where the fade margin would need to be much higher to compensate for blockage.

Even using space diversity at the satellites (e.g., 2 geostationary satellites on largely separated orbital positions as proposed by two DARS system proponents) can only partially mitigate such blockage since both would be received with minimal fade margins, producing two signals close to the receiver threshold, hence still resulting in minimal margin to combat blockage. The principle of using two

geostationary satellites in this case is to decorrelate the fading on both paths so that the resulting availability is increased. This is expected to be beneficial in rural environment and on highways where a reasonably high availability is already possible (e.g., 90% availability on each path would translate, at best, into 99% overall availability if the two paths were to be totally decorrelated, a likely example is the elimination of system drop-outs caused by road signs). Fade correlation would be minimized through maximizing the orbital separation between the two satellites within the practical limits of the geometry since this would tend to translate into lower elevation angles from the satellites, thus more blockage). In an urban environment, the improvement in service availability is likely to be much constrained since the availability on each path will be much lower and the correlation of the fades on the two satellite paths is likely to be much greater; the worse case being a full fade correlation which would not provide any improvement over the single satellite case.

Furthermore, depending on where the receiver would be located and the geometry of the satellite transmit paths, the difference in delay between the two signal paths may be quite extensive, therefore creating other problems at the receiver, similar but more extensive than those that will be reported later relating to the size of the time-domain equalization window in the case of a single carrier modulation, and the extent of the guard interval in the case of a multi-carrier modulation.

The only way to effectively compensate for urban blockage is by being able to locally produce a large excess power to allow reflected paths with still high enough signal strength to reach the receiver to cover areas that cannot normally be reached through line of sight. This can only be done through the use of **terrestrial repeaters**.

This is a form of **space diversity** which provides the receiver with new sources of signal for the same service. Typically, the polarization used for satellite transmission is circular to remove the effect that Faraday rotation would have on tilting the linear polarization as well as the effect of the geometry which would make the polarization tilt different in different geographical areas. However, vertical polarization would likely be used for terrestrial transmission for convenience in the receive antennas on cars and portable receivers as well as ease of implementation at the transmitter. The use of such space diversity at the transmit end (i.e., satellite plus terrestrial repeaters)implies that the receiver will need to be equipped with a high quality circularly polarized antenna with maximum gain towards the elevation angle of the satellite and some form of vertically polarized receiving elements with some gain towards the horizon for receiving signals from the terrestrial transmitters.

The terrestrial transmitters could use a different frequency than the satellite transmission to supplement the satellite coverage but then the receiver would have to contend with two RF front ends tracking the level of the signals and switching to the one with the highest strength. This would also result in the use of more frequencies for the same service, and thus less efficient use of the spectrum. On the other hand, if the same frequency is used, the terrestrial signal would be received as an echo of the satellite signal. This "active" echo would typically render the multipath environment more severe wherever both the satellite signal and the repeater signal are received and even more so where several active echoes from several terrestrial on-channel repeaters are receivable. The resulting condition is rather complex and very similar to the case of multi-transmitter coverage in the terrestrial case as described in detail in the ITU-R Special Publication on DSB [ITU-95]. It is felt that a more detailed description of this situation in the case of a hybrid satellite-terrestrial coverage is warranted in the current context.

4.4.4 Satellite and terrestrial repeaters

The path geometry involved for a satellite coverage supplemented by terrestrial repeaters is illustrated in Figure 4.4. At first glance, it appears that with this simple system configuration, normal

city coverage can be added to the satellite coverage in an elegant way without any drawback. It can be observed that, from the point of view of the receiver, the two signal components arrive at different times and the delay between the two signals increases as a function of the distance from the terrestrial repeater. The channel impulse response at the receiver input depicted in Figure 4.4 shows the delays and relative signal strengths as the vehicle moves away from the repeater.

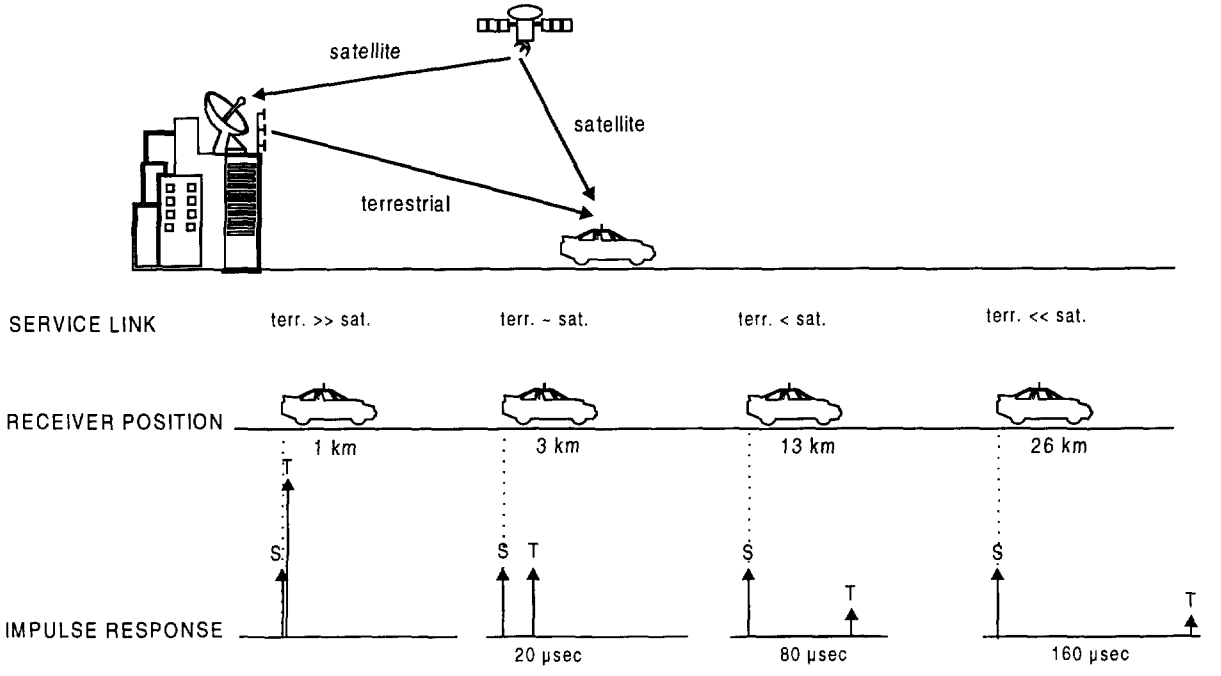

Figure 4.4: Path geometry and related active echo position in a hybrid satellite/terrestrial service

The addition of the "active echo" from the terrestrial repeater has a major impact on the channel conditions. The resulting channel impulse response is characterized by the presence of a strong multipath component that has a delay value exceeding by far the typical delay spread values found in any other multipath environments. Limiting again the discussion to three types of environments, we can examine more closely the impulse response in the urban area, the suburban area and the open rural area. Also, for the moment, it is assumed that only one terrestrial repeater is employed for terrestrial augmentation. The repeater receives the satellite signal (circular polarization is assumed) and simply retransmits it after some filtering and amplification, using a vertically polarized transmit antenna. No frequency conversion is done. This means that the receiver does not have to look for the complementary signal on a different frequency. It is a transparent process.

Another aspect to keep in mind at this stage is that the receiver expected to operate in a hybrid satellite/terrestrial service environment could be equipped with either a special dual antenna/front-end sub-system that can detect the presence of a terrestrial signal and switch from the circularly polarized satellite antenna to the linearly polarized terrestrial antenna or it could be equipped with a compound antenna which has maximum circularly polarized gain at the elevation at which the satellite is seen (e.g., 5 dBic) as well as some vertical gain towards the horizon (e.g., 0 dBi), the signal from these two receive antenna sub-systems being added passively. For simplicity sake, the second implementation is preferred in the following analysis. A simple circularly polarized antenna, optimized for satellite reception, with elevation angles ranging from 30 to 55 degrees with an additional vertical monopole for terrestrial reception is assumed hereafter.

Back to the case study: a SCPC satellite service is received by a vehicle going from a rural community towards the downtown area of a large city. In the rural area, it can be assumed that the channel environment is the same as that of the situation described above (i.e. satellite alone, no terrestrial repeater being used) except that for some parts of the coverage area the signal emitted by the terrestrial repeater will be present, probably very weak due to the long distance to the transmitter. At places where the terrestrial signal is useable, (probably near the suburban area), the resulting channel is characterized by a strong satellite signal accompanied by a weak terrestrial signal with some excess delay (see Figure 4.5). The delay value depends on the geometry of the links between the receiver, the satellite and the terrestrial repeater. The largest excess delays are encountered when the vehicle is moving in the direction of the satellite with respect to the repeater. On the opposite side of the repeater, the excess delay values are much shorter since both signals have traveled more or less the same path. This shows that the receiver will have to cope with a non-negligible multipath component that can have excess delay values ranging from short to extremely long. Again, the zone affected by the presence of both signals is limited to areas where the terrestrial signal has sufficient strength to overcome the path loss and the discrimination (gain and polarization) from the receiver antenna. In short, the zone affected will depend on the emitted power of the terrestrial repeater.

The channel for this particular environment can be depicted by a single impulse whose amplitude fluctuates from a maximum level (line-of-sight) to practically zero when some obstruction is encountered along the road. The passive multipath ("passive echoes" due to reflection surfaces around the receiver antenna) will typically be negligible since it will be below the noise threshold of the receiver due to the relatively small operation margin of the satellite system. As seen before, this channel behavior is representative of the Rician model. This single impulse is shifted in frequency by the Doppler shift, upward if the vehicle moves towards the satellite and downward if the vehicle moves in the opposite direction with respect to the terrestrial repeaters. Then, with the addition of a terrestrial on-channel repeater, a second impulse is added to the channel impulse response representing the signal received from this repeater. The relative amplitude of this pulse varies according to the physical distance to the repeater, and to the amount of blockage present (log-normal model).

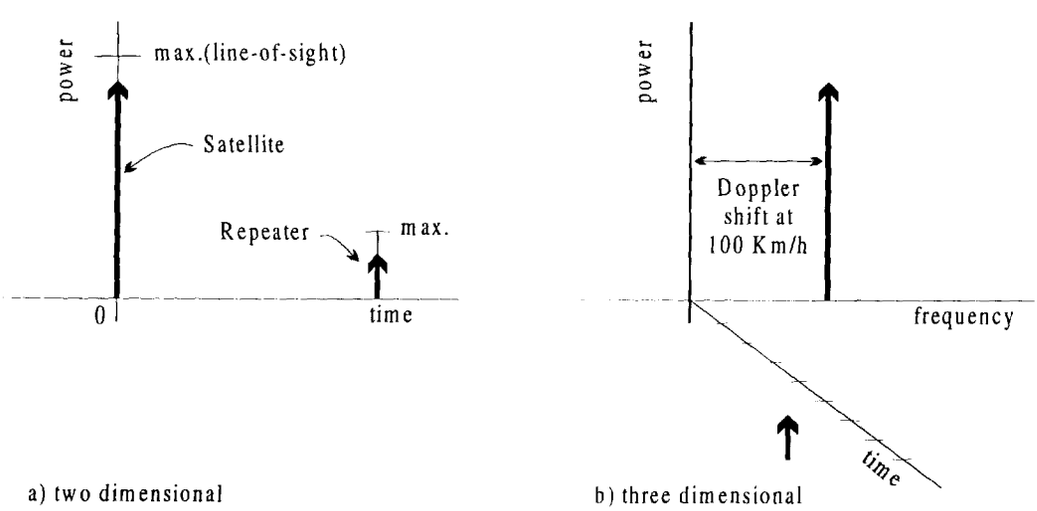

Figure 4.5: Simplified impulse response of a rural open channel, hybrid satellite/terrestrial service.

As the vehicle approaches the suburban area, the satellite signal fades more frequently due to blockage by buildings and trees. The terrestrial signal starts being useable to fill these service holes but it has just enough fade margin to meet the requirements in the suburb area. The non-desired

effect of the presence of the terrestrial signal is that it creates a severe multipath environment at all locations where both the satellite signal and the terrestrial signals are received at a useable level. The active echo generated by the terrestrial repeater has a long delay exceeding typical suburban delay spread values in a portion of the coverage area (see Figure 4.6a) . Its Doppler shift will typically exceed that of the satellite signal because of the low elevation angle to the terrestrial transmitter (Doppler shift is proportional to the cosine of the elevation angle of arrival of the signal). Furthermore, there will be passive echoes from the repeater in a terrestrial environment which will be received at various amplitudes, typically according to the Rayleigh model in an urban/suburban environment (see Figure 4.5a). In addition, depending on the direction of the vehicle displacement relative to the repeater and angle of arrival of these passive echoes, these pulses will be shifted in frequency upward and downward (see Figure 4.5b). This is what creates the Doppler spread effect at the receiver which cannot be compensated by the receiver AFC since the shifts are in different directions. The channel can be characterized as a mixture of Rician and Rayleigh channel conditions (see Figure 3.6b).

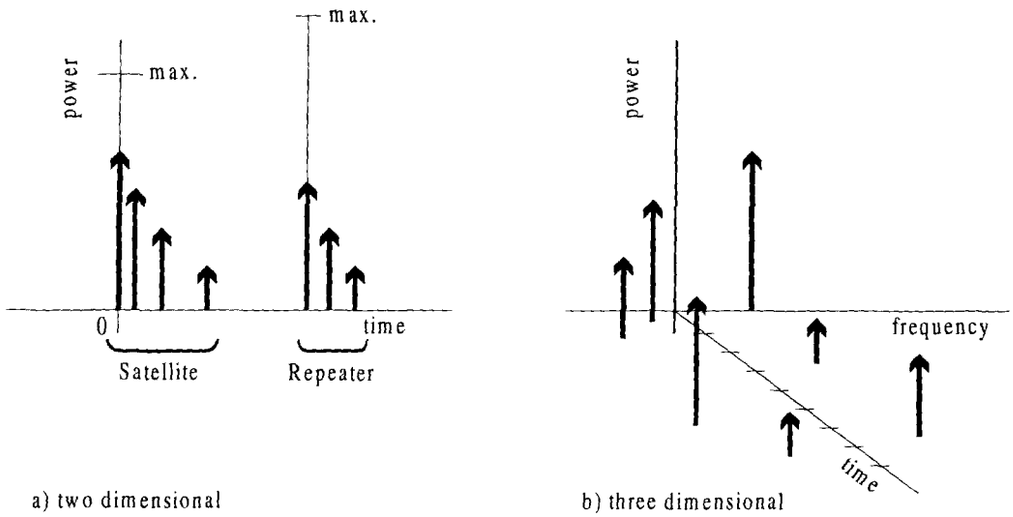

Figure 4.6: Simplified impulse response of a suburban channel, hybrid satellite/terrestrial service.

When reaching the downtown area, the dominant signal is received from the terrestrial repeater. In principle, it has sufficient fade margin to adequately cover the neighboring area by itself whether the vehicle is moving or stopped. Blockage from buildings causes deep fades for both direct signals but the reflected waves from the repeater signal are strong enough to be used by the receiver and compensate for the fades on the direct signal path (see Figure 4.7a). Their phase is random and so is the Doppler shift. The vehicle speed is low and the Doppler effect is small when compared to the rural environment. This situation is well represented by a Rayleigh channel model (see Figure 4.7b).

Figure 4.8 summarizes this discussion in a graphical way. This illustration also reveals the relative size of the areas affected or characterized by the three different channel models.

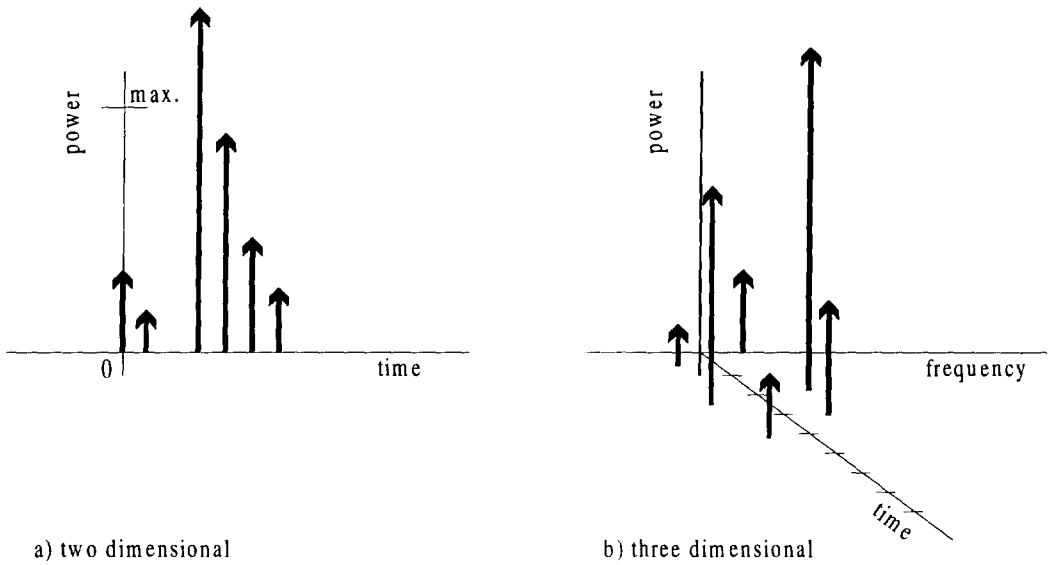

Figure 4.7: Simplified impulse response of an urban channel, hybrid satellite/terrestrial service.

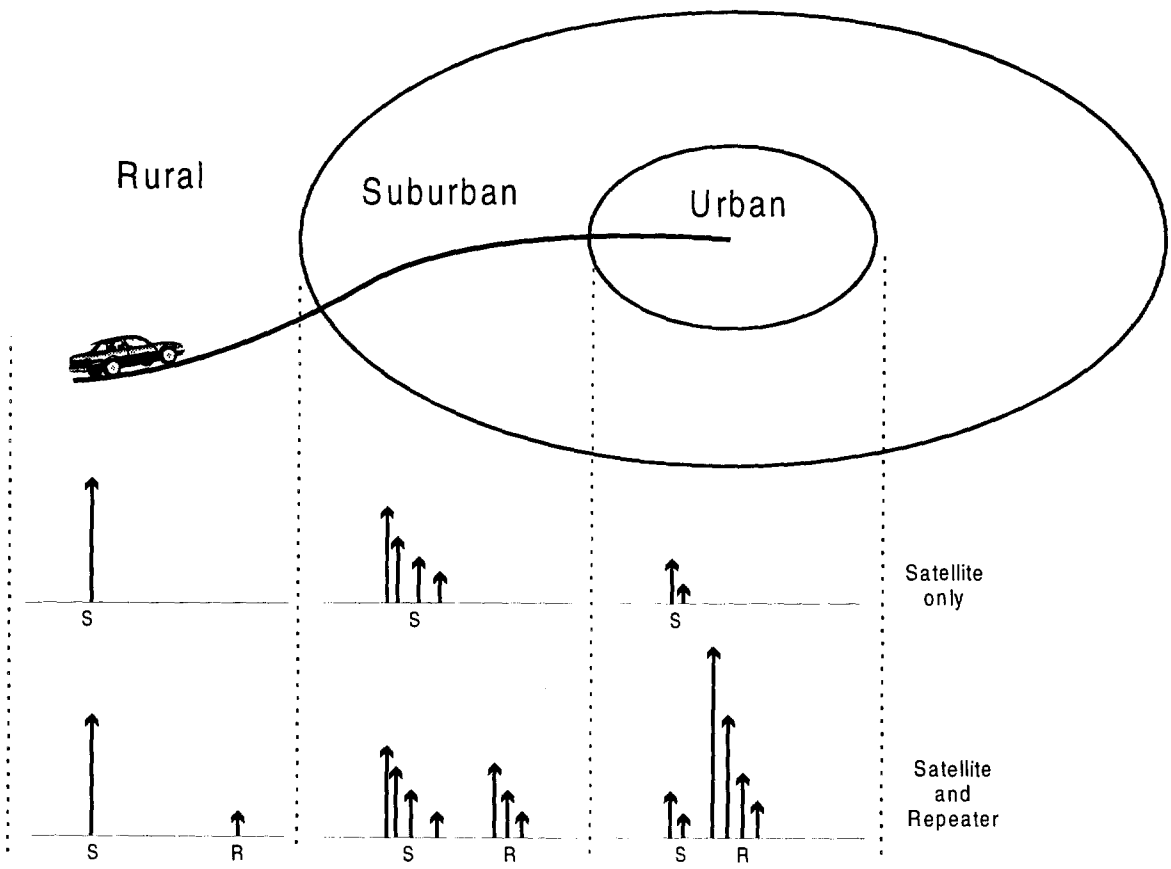

Figure 4.8: Impulse responses in the three types of environment

4.5 Mitigation techniques to counter transmission channel impairments

In Section 4.4.2, it was made clear that the mobile environment is characterized by the presence of large fades and strong multipath signal components. If no mitigation technique is employed, this results in frequent service interruptions due to flat fading of the signal (shadowing, normally modeled by a Log-normal statistical distribution) and frequency selective fading (multipath, modeled by a Rayleigh statistical distribution). These two fading conditions must be treated separately as they require different solutions.

4.5.1 Case of a flat fading channel

Flat fading is a condition where the whole signal bandwidth is equally faded. An example of flat fading is the effect on the reception of an obstruction created by a large building along the street. During the fading period, the information is lost. Typically, bit error correction techniques allow the receiver to reconstruct this information, or part of it, as long as the fade does not exceed the time interleaving depth implemented in the channel coding. If it exceeds this maximum time such as in the case of a car stopped at a red light, there is nothing that can be done to recover the signal except through space diversity. In this case of blockage, receive antenna diversity would not help much since the area of blockage is likely to be larger than the spacing that can be achieved between multiple receive antennas mounted on a car. Space diversity at the transmitter is thus necessary and this is the reason for the need of on-channel repeaters to try to produce seamless coverage even in obstructed environments. The local terrestrial repeater will be able to produce enough excess power to allow reflections to reach the receiver with high enough strength to allow reception even though the direct paths are obstructed.

4.5.2 Case of a selective fading channel (multipath)

Frequency selective fading is caused by the presence of strong reflected signals which create a very complex standing wave pattern through which a car has to go. Since the repetition cycle of the signal is in the order of the wavelength, the channel variability created through the motion of the car can be very high. This is the time domain explanation of a Rayleigh frequency selective channel which suffers Doppler spread. In the frequency domain, this condition creates nulls at specific frequencies in the signal bandwidth and the channel is therefore considered frequency selective. The location of these nulls vary with time due to the displacement of the vehicle. This variation can be very fast depending on the speed of the vehicle. At low vehicle speed, the tracking of the channel conditions is rather easy even though time interleaving becomes less effective. Well optimized modulations will be able to recover the signal properly in this case except in the presence of a high amplitude close-in reflection. In such case, if the reflection is close enough, a flat fading will occur at the receiver and, if the vehicle does not move fast enough, time interleaving, as explained above will not be able to compensate for this fade. An example of this occurs when a vehicle is brought to a standstill at a stop sign. Even though the physical distance to cover to get out of this flat fading is small, typically in the order of the wavelength (13-20 cm), this can occur for a certain time, exceeding the time interleaving depth of the modulation. The condition for such a flat fade to occur is related to the coherence bandwidth of the channel which is directly related to the excess delay of the reflection by the following simplified formula:

$$T \approx 1/BW$$

Several field measurements have been conducted to characterize multipath at UHF from a single terrestrial transmitter. In [KAH-94] for instance, 80% of all the delay spreads measured at 1.5 GHz in a wide variety of areas (rural, suburban, urban, dense urban, wooded) had a value smaller than

5.14 μsec. In measurements made at 900 MHz in four US cities [RAP-90], the delay spread was smaller than 5 μsec approximately 78% of the time, which is in good agreement with the measurements at 1.5 GHz in [KAH-94]. Measurements made in London, UK at 900 MHz [GUR-87] over two 1 km runs showed that nearly 100% of the delay spread values measured were less than 5 μsec. In typical sectors of a hilly area, measured delay spreads were less than 5 μsec 85% of the time while this value increased to 9 μsec over "bad" sectors [GUR-87]. Although the measurements reported here were made at 900 MHz and 1.5 GHz, it is reasonable to assume that they would hold true at 2.3 GHz as well. These field measurements show that radio channels with coherence bandwidth of 200 kHz or more occur quite frequently in non-hilly environments.

As an example, a 200 kHz bandwidth signal can experience flat fading with any high amplitude echo with excess delay of less than approximately 5 μsec whereas a 1.5 MHz bandwidth signal can experience such flat fading for echoes with excess delay of approximately 0.67 μsec. Most high amplitude echoes typically fall in the 1 to 6 μsec range in the urban and suburban cases; this is the reason why a wide bandwidth DAR system has a clear advantage in terms of signal robustness in these environments. Studies looking at the impact of signal bandwidth on received signal levels at L-band have shown that an *optimum* signal bandwidth seems to be around ***2 MHz***. [ITU-91a]. In the case of such a flat fading, there are, however, other means to alleviate the problem. Time diversity will be effective if the car is in motion, creating a time varying channel. However, if the car is stopped, space diversity has to be used, either at the receiver with receive antenna diversity or at the transmit end with on-channel repeaters.

At high vehicular speed, time interleaving would help to average the errors but the channel conditions vary so much that a large amount of errors is constantly produced due to the receiver not being able to track the highly varying channel conditions. There is no means to alleviate such condition except by the presence of a much stronger signal from a local repeater (creating an artificial local Rician channel condition) which would allow the receiver to lock with its AFC, discarding the much lower multipath components which make the channel too complex to be decoded. This hard limit for which, unlike in the previous channel conditions, there is no other diversity means, is the reason for the **intrinsic limit in carrier frequency for mobile reception** in a complex environment. The consequences of this, especially in the context of a satellite service complemented by terrestrial on-channel repeaters will be explained in the following sections.

4.5.3 Existing technologies to counter transmission channel impairments

The channel conditions prevailing in a mobile reception environment were described in Section 4.4.2 and 4.5.1. With the recent advances in DSP technology, a variety of techniques previously considered as theoretical and impractical are now feasible. This makes it possible to devise powerful error detection and correction methods, robust digital modulation and adaptive mitigation techniques such as channel estimation and equalization as well as the use of multi-carrier modulation.

There are a number of mitigation techniques, as seen above, to correct for the harsh environment resulting from mobile reception: time diversity (time interleaving), frequency diversity (frequency interleaving) and space diversity (receive antenna space diversity and transmit antenna space diversity). These tools are available to combat the various channel conditions but the price to pay for the resulting robustness is usually in the form of a loss of channel capacity, increased complexity and processing delays and receiver complexity, as well as increased power consumption at the receiver. The best system is therefore the one that allows the best set of trade-offs among these various aspects.

5. Multi-carrier modulation (COFDM)

One of the main candidate modulations for DAR systems is the Coded Orthogonal Frequency Division Multiplex (COFDM) modulation as used in the Eureka-147 DAB system [ETS-95].

5.1 System description

In digital transmission, the performance of the system is determined by the capability of the channel coding and modulation to adapt to the impairments of the transmission channel. This section will describe the channel coding and modulation scheme employed in a multi-carrier modulation to work in a satellite as well as terrestrial environment. As reviewed in detail in Section 4, for the specific application of satellite DARS (L- or S-band) with complementary terrestrial on-channel repeaters aimed at producing seamless mobile reception, the most problematic channel impairment is certainly fading due to shadowing and multipath. In a frequency-selective fading situation, where only a portion of the signal spectrum is faded, the conventional approach associated with single carrier modulation is to consider a form of signal ***equalization*** to reduce the inter-symbol interference (ISI) that results. This will be explained further in Section 6.

A very effective approach to dealing with frequency-selective fading is to segment the signal bandwidth into N carriers, such that each is flat faded, and then separate the data stream into N sub-streams, each assigned to a carrier and having a symbol period N time longer. The objective is to:

- transparently survive the loss of a certain percentage of narrow carriers in the channel;
- minimize inter-symbol interference.

This approach is referred to as multi-carrier modulation, with a very specific implementation known as Orthogonal Frequency Division Multiplexing (OFDM).

The merits of multi-carrier OFDM are examined next.

5.1.1 OFDM

As mentioned previously, by segmenting a frequency-selective faded channel in the frequency domain into N orthogonal carriers - orthogonal frequency division multiplexing - it is possible to have multiple flat faded carriers, where some are flat faded some of the time, but never all of them. When used with proper coding and interleaving, it is possible to achieve a system that can be decoded correctly even when a certain percentage of the carriers is completely lost due to flat fading. This is an effective way to provide frequency diversity where some frequency selective fading is experienced in the transmission channel and time interleaving cannot help because the vehicle is moving at a relatively slow speed.

As well, the data stream is separated into N sub-streams, each assigned to a carrier and having a symbol period N times larger and a data rate N times smaller. This leads to a reduction in multipath ISI. Such ISI can actually be totally removed with the use of a guard interval in the transmission during which the receiver ignores the signal from the channel (see discussion of *guard interval* below) as long as all the echoes that fall within this guard interval.

The design objective is to achieve a sub-channel bandwidth that guarantees flat fading while at the same time stretching the symbol period so that it is much longer than typical echo delays. Both of these objectives are achieved by selecting a value of N sufficiently large. This segmentation of the

data into sub-channels is performed with an inverse Fast Fourier Transform (FFT) at the transmitter and the recovery of the data is done through a FFT chip in the receiver.

If the system is properly designed and the numbers for sub-channels and their individual bandwidths are properly selected, the individual sub-channels will suffer from flat fading. ***Interleaving in the frequency domain*** using a pseudo-random sequence will ensure that flat fades in successive sub-channels will not correspond to loss of successive data symbols; this provides for randomization of the errors caused by multipath fading. ***Error randomization*** is important because channel decoders (using the Viterbi decoding algorithm) in the receivers are better able to handle randomly distributed errors than clustered errors. Reordering symbol errors so that the decoder perceives them as independent maximizes the decoding efficiency. Likewise, ***interleaving in the time domain*** using a similar pseudo-random sequence ensures that time-domain impairments will not correspond to loss of successive data symbols; this further ensures error randomization.

Without appropriate ***coding*** that provides adequate recovery from lost symbols after de-interleaving in time and frequency, the advantage of OFDM could not be retained. Coding in conjunction with frequency and time interleaving provides a link between bits transmitted on separate carriers of the signal spectrum, in such a way that information conveyed by faded carriers can be reconstructed in the receiver using coding links relating them to information from undamaged carriers.

Coding and interleaving applied to OFDM can be considered as a method of averaging local fades over the whole signal bandwidths and over the time interleaving depth. It is important to recognize that coding and interleaving are essential characteristics of any digital transmission scheme, not limited to the OFDM approach.

If a constant amplitude constellation (i.e., *m*-PSK, QPSK, DQPSK, etc.) is used, there is no need to equalize the individual sub-channels, because the signal phase (not the signal amplitude) carries the information. Furthermore, if a differential encoding approach (i.e., DQPSK) is used, phase reference information to help the receiver synchronize is not necessary, as the phase difference between successive symbols contains the information. For these reasons, ***DQPSK*** modulation is the preferred modulation for broadcasting services targeted to mobile reception. In the case of a satellite only broadcast system, coherent demodulation would be preferred since it allows a reduction of 3 dB in satellite power. However, if a hybrid approach is to be implemented with terrestrial repeaters used to complement the satellite coverage in shadowed areas, differential modulation will have to be used since excessive overhead would be required to train the receiver in a terrestrial mobile context (Rayleigh channel).

In order to further minimize the impact of ISI due to multipath fading, a buffer is inserted between successive time symbols. Referred to as the ***guard interval***, this buffer typically has a time duration equal to 20% of the total transmitted symbol. This is equivalent to a 1 dB power loss in the transmission, but the resulting gain from ISI elimination, especially in very difficult multipath environments is compensated many-fold. At the receiver, the signal energy occurring during this buffer period is ignored, and all energy occurring within the useful symbol period is considered as constructive energy.

The COFDM system with interleaving and guard interval is designed to be robust in a multipath environment where naturally occurring echoes exist. It is able to handle any echoes of any amplitude and time delays within the guard interval. This characteristic can be taken advantage of by creating active echoes, in this context with ***on-channel repeaters***, to act as gap-fillers, coverage extenders or as part of a synchronized or non-synchronized single frequency network (SFN) in the case of terrestrial DAR broadcasting as described in the ITU-R Special Publication on DSB [ITU-95b]. The

distance between transmitters must respect the condition that signal propagation time must not exceed the guard interval, otherwise the receiver will see some of the signals falling outside the guard interval and they will start producing ISI.

As examples of COFDM configurations with signal bandwidth, number of carriers and guard interval duration, Table 5.1 presents the four possible modes of operation of the Eureka 147 DAB system described in reference [ETS-95].

	Mode I	**Mode IV**	**Mode II**	**Mode III**
Number of carriers	1536	768	384	192
Carrier spacing [kHz]	1	2	4	8
Useful symbol duration [μs]	1000	500	250	125
Guard interval duration [μs]	246	123	62.5	31.25
Signal bandwidth [kHz]	1536			
Modulation	DQPSK			
Raw data capacity [kbit/s]	2304			
Useful data capacity [kbit/s]	1152 (with rate ½ error correction coding)			

Table 5.1: Transmission Modes for the COFDM portion of the EUREKA-147 system

The carrier spacing will determine the impact of Doppler spread interference, but this is also a function of operating frequency and vehicle speed. The impact of the Doppler spread sets the upper limit for the selection of the value of *N*: too large a value will result in unnecessary performance reduction due to Doppler interference. In fact, a very basic trade-off in the context of the COFDM modulation is the sensitivity to Doppler spread versus the extent of the guard interval. Typically, the longer the guard interval is, the larger the separation between terrestrial repeaters can be. The number of these repeaters to cover a given area will be related to the size in the guard interval as a square function. This is the reason why the guard interval needs to be stretched as much as possible within the constraints of the Doppler spread. Also, it was found that for a given percentage of guard-interval versus total symbol period, the maximum speed of a vehicle allowed before the Doppler spread starts to affect the quality of the reception is linearly related to the carrier frequency.

In order to allow the system to operate properly at 2.3 GHz, the speed of the vehicle would have to be reduced by a factor of 0.6 with respect to the speed allowed at 1.5 GHz. Another way would be to reduce the symbol duration by a factor of 0.6 so that the faster channel transitions due to the increased Doppler spread at this higher carrier frequency can be accommodated with an equivalent system performance. This would allow a smaller number of carriers and consequently, a larger carrier spacing. If the same relationship is kept between guard interval and symbol period in order to keep the same channel throughput, the guard interval would therefore be reduced by a factor of 0.6. In a terrestrial coverage case, this would mean an increased density of repeaters of $(1/0.6)^2 \approx 2.8$ when consideration of propagation is neglected.

Yet another approach would be to favor an increase of signal bandwidth to maintain the same throughput and Doppler performance with an optimal repeater density. In this situation the first constraining factor is the symbol duration which must be kept short to avoid Doppler spread effects. The guard interval can be adjusted to a larger percentage of the symbol duration to keep the same repeater spacing. This has the effect of reducing the channel capacity but it can be compensated by an increase of channel bandwidth. For example, if the symbol duration is reduced by a factor of 0.6, the guard interval/symbol ratio is increased from 20% to 30%, and the carrier spacing is enlarged by

a factor of 1.66 (i.e. 1/0.6). This arrangement yields, at 2.3 GHz, an equivalent data throughput and an equivalent robustness to Doppler spread, as experienced with Mode II at L-band, but note that the signal bandwidth had to be increased from 1536 kHz to 1740 kHz.

The effect of frequency scaling in the case of satellite coverage augmented by terrestrial repeaters will be covered in Section 5.2.

5.1.2 COFDM and satellite transmission

Studies were carried out on the transmission of COFDM in a non-linear transponder typical of satellite transmission. It was found that in order to keep the sidelobes down to 20 dB, the transponder has to be operated at 2.0 dB output back-off in the case of COFDM compared to 0.3 dB output back-off for a single carrier constant envelope modulation. At an output back-off of 2 dB, the required Eb/No value for COFDM at the receiver to maintain a BER of 10^{-4} is only 1 dB higher than in the case of an ideal linear amplifier [LE-95]. This result was found for both a TWTA and a SSPA. This demonstrates that meeting the sidelobe rejection level is more constraining than the in-band error generation. There is therefore some cost at using COFDM over satellite but this is amply compensated in the case of a hybrid satellite/terrestrial by the fact that a common modulation scheme can be used for both satellite and terrestrial transmission to produce seamless coverage. Although coherent demodulation is the preferred choice to minimize the satellite transponder power requirement, differential modulation would need to be used in a hybrid operation to cover for the mobile reception from the terrestrial repeaters.

5.2 Coverage case study for multi-carrier modulation

This section looks at the coverage impact of using terrestrial on-channel repeaters to complement mobile reception of satellite transmission of a multi-carrier modulation using the Eureka 147 DAB system as a model, operating in Transmission Modes II and IV at L-band and a new Mode IV scaled according to the carrier frequency at S-band for the purpose of the comparison.

Assumptions:

- ITU-R Recommendation 370 propagation model with 50 m terrain roughness factor for rural reception; equivalent to FCC propagation curves [ITU-86a]; including scaling of the propagation prediction in terms of receive antenna height (1.5 m rather than 10 m) and it terms of frequency [ITU-91b];
- Okumura-Hata fading model [HAT-80] for urban reception;
- satellite downlink budget similar to that presented in the ITU-R Special Publication on DSB [ITU-95b];
- satellite fade allowance of 5 dB;
- signal availability for 95% of locations based on log-normal distribution with 3.9 dB standard deviation for satellite and 5 dB for terrestrial;
- omnidirectional receive antenna at 1.5 m height AGL with 5 dBic satellite gain and 0 dBi terrestrial gain;
- minimum required C/(N+I) = 10.4 dB for a BER of 10^{-4}, including allowance for Doppler spread, hardware implementation, satellite uplink degradation and interference;
- receiver noise figure of 3 dB;

- 1 dB of margin is set aside to deal with the potentially destructive signals generated by hybrid terrestrial repeaters.

5.2.1 Illustrative coverage case

The signal path geometry of the DARS system complemented by a terrestrial on-channel repeater is illustrated in Figure 5.1 for increasing values of receiver distance from the terrestrial repeater, also including the relative signal levels and propagation delays in relation to the Transmission Mode II guard interval (62 µsec).

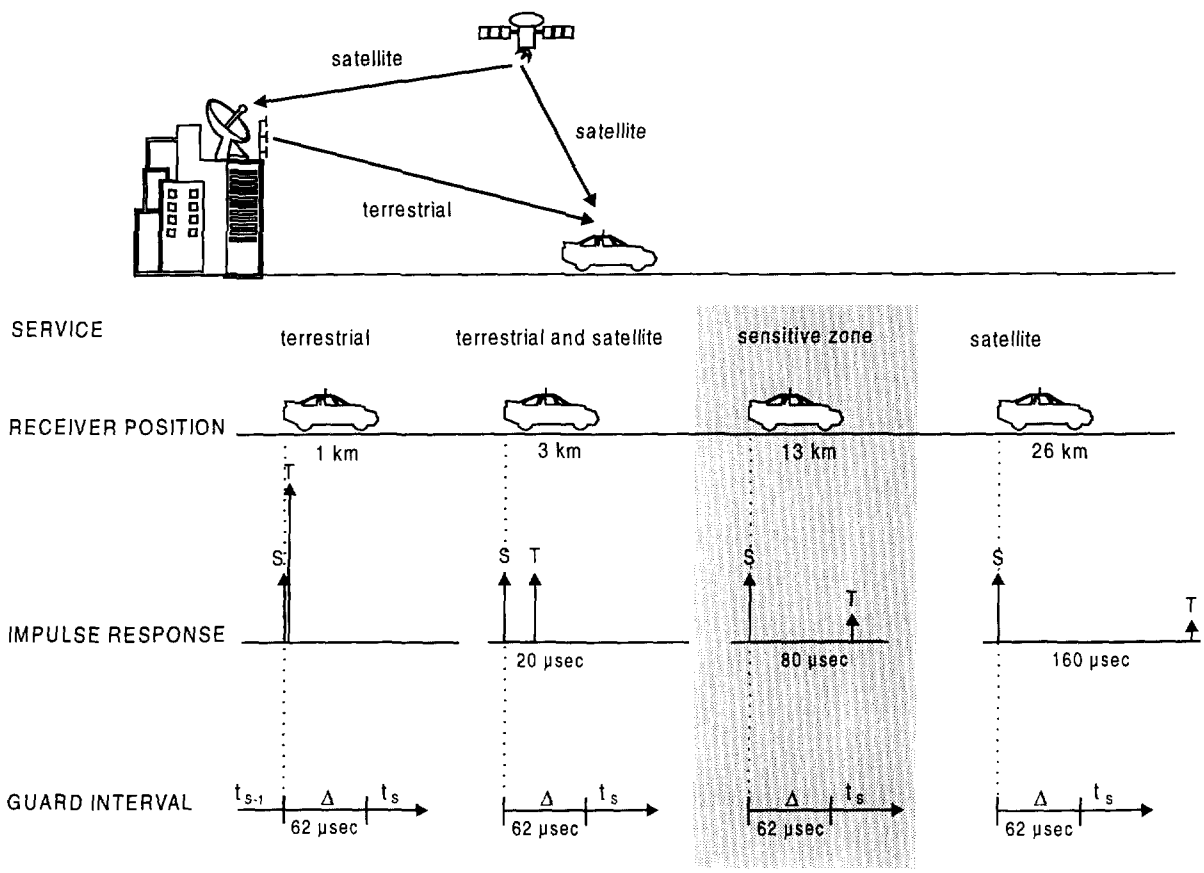

Figure 5.1: Signal path geometry of satellite DAR complemented by a terrestrial on-channel repeater.

In the vicinity of the terrestrial repeater, all signals will be received within the guard interval, such that all signals will be seen as constructive through statistical signal addition. As the receiver moves away from the repeater, some signals start appearing outside of the guard interval and thus can become destructive. In this sensitive zone, the degree of interference will depend on the relative signal levels, and excessive interference will result in coverage gaps or interference areas`, appearing near the repeater in the direction of the satellite. It is possible to design the repeaters in such a way that this interference is controlled and has a negligible impact on the service coverage. As the receiver moves further away from the repeater, the interference problem starts disappearing as the repeater signal level becomes sufficiently low relative to the satellite signal level.

When interference does occur, the resulting interference area is delimited first by the guard interval duration, setting the inner limit of the interference area (the location closest to the repeater where interference impedes service) beyond which signals start falling outside the guard interval and creating interference. At this point, the interference becomes objectionable rather abruptly, as depicted in Figure 5.2.

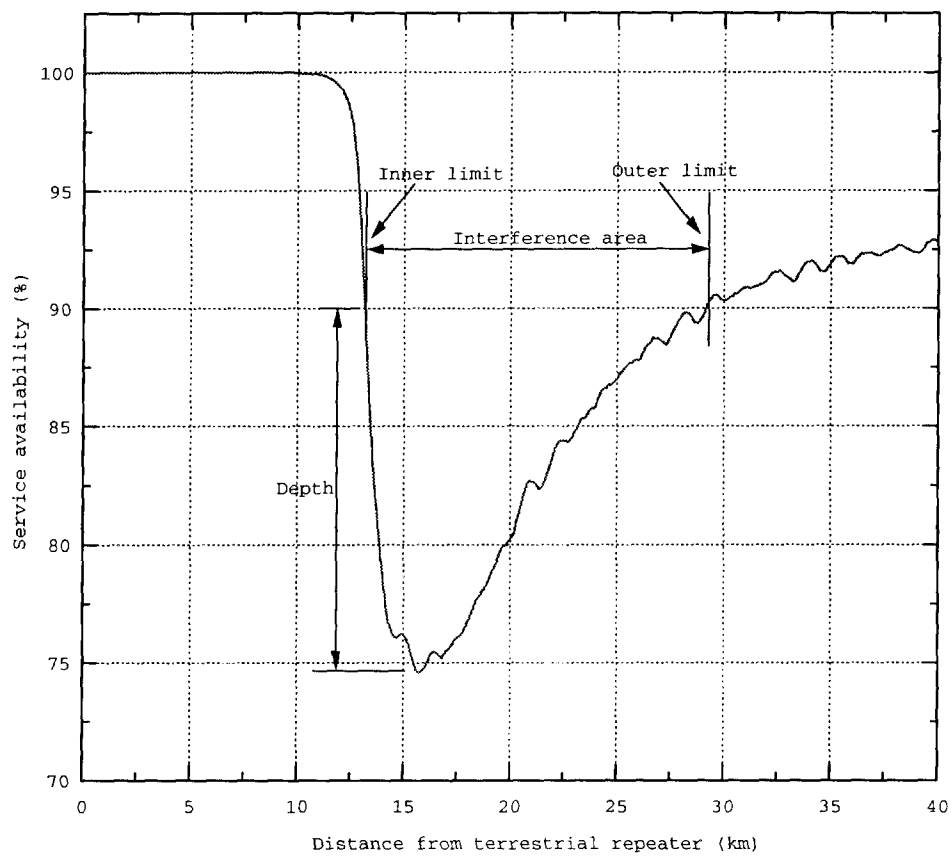

Figure 5.2: Service availability along a route from the repeater location toward the satellite.

Figure 5.2 shows a curve that corresponds to the service availability for a vehicle traveling away from the terrestrial repeater, across the interference area and eventually in the rural area served by the satellite. The service availability decreases abruptly as soon as the terrestrial signal falls outside the guard interval (i.e. at the inner limit) while near the outer limit, the service availability comes back very smoothly to the rated service objective (in this case: 90%). From this observation it can be intuitively concluded that minor changes of the repeater parameters will have an important effect on the smooth outer limit while the availability of service near the inner limit will be affected only by major changes in the broadcast system configuration (i.e., the guard interval duration). The depth of service availability in the interference area offers some interest in that it is a measure of the severity of the potential loss of service. In this case, the service availability went from 100% near the repeater down to 75%. It can also be observed that the magnitude of the interference area should be expressed not only by its surface but also by its depth.

Unlike the inner limit, the outer limit (i.e., the location furthest from the repeater where interference impedes service) does not depend on the guard interval duration, but rather on the relative repeater

signal level, such that it is still destructive with respect to the satellite signal, but sufficiently weak to meet a predetermined carrier-to-interference ratio required by the receiver. In these outer locations, the excessive radiated power from the repeater is the main cause of interference and, as seen on Figure 5.2, this interference situation improves slowly with the increase in distance from the terrestrial repeater.

In summary, the size and position of the interference area is a function of the guard interval duration and of the repeater signal energy seen by the receiver, which is, in turn, a function of the effective radiated power (ERP) and the antenna height of the terrestrial repeater. A decrease of the terrestrial repeater ERP will quickly bring in the outer limit of this interference zone whereas the inner limit will be pushed out by an increase in the guard interval duration.

The relationship between the interference area size and the ERP for various antenna heights (EHAAT: effective height above average terrain), satellite signal elevation angle and guard interval duration was investigated. Table 5.2 provides a summary identifying the conditions for which the interference area can be avoided.

EHAAT	**Mode II**		**Mode IV**	
[m]	**Elevation angle**		**Elevation angle**	
	30°	**60°**	**30°**	**60°**
25	110 W	300 W	4000 W	10000 W
50	20 W	70 W	1000 W	2300 W
100	4 W	18 W	250 W	700 W
200	< 1 W	3 W	40 W	180 W

Table 5.2: Maximum allowable effective radiated power (ERP) from the terrestrial on-channel repeater to avoid an interference area, as a function of antenna height (EHAAT), satellite signal elevation angles and guard interval duration [Mode II: 62 μs, Mode IV: 123 μs], assuming an omnidirectional re-transmit antenna.

The dominant factor is the guard interval duration. By changing from Mode II to Mode IV and thus doubling the guard interval duration (from 62 to 123 μsec), the inner limit of the interference area is pushed back further from the repeater (by a factor of 2), into an area where the potentially interfering repeater signal provides much less energy, resulting in considerably lower interference levels. It is therefore much easier to avoid the interference area with Mode IV than with Mode II.

In order of importance, the following parameters also affect the interference area: repeater antenna height (EHAAT), satellite signal elevation angle and radiated power. Of these, repeater antenna height and radiated power can be easily optimized in the design phase of the DARS network. Note the constraining limitation in ERP (4 to 18 W) for Mode II at 100 meters antenna height which would result in a very small area covered by a terrestrial repeater. In such a case, more repeaters would be needed to blanket a given area. Since the 30° elevation angle represents a worst case for CONUS coverage, the case studies reported below will concentrate on this elevation angle.

As an illustration of this approach, consider a hypothetical geostationary satellite DARS system based on the Eureka 147 modulation system operating in Mode II at L-band, with a high power omnidirectional repeater located in downtown Toronto. The ERP and EHAAT of the single repeater were adjusted to cover the metropolitan area of Toronto. This resulted in a 2000 W ERP and 200 m EHAAT. This excessive ERP, as compared to the values in Table 5.2 creates, as is to be expected, a huge interference area which has the shape of a crescent as shown in Figure 5.3 for a satellite transmission received from the South-South-West direction. In fact, Figure 5.2 could be understood as giving a profile of the interference situation for a vehicle moving from the repeater towards the direction of the satellite. By using a dozen low power omnidirectional repeaters, properly located in the city, it is possible to make the interference area disappear. This is shown in Figure 5.4, where twelve repeaters are operated at 20 W ERP and 50 m EHAAT; and the contour line indicates where the terrestrial repeaters offer coverage as opposed to the satellite. For this illustrative example, the ITU-R PN. 370 [ITU-86a] "augmented" to make it applicable to 1.5 GHz and to a 1.5 meter receiving height was used [ITU-91b].

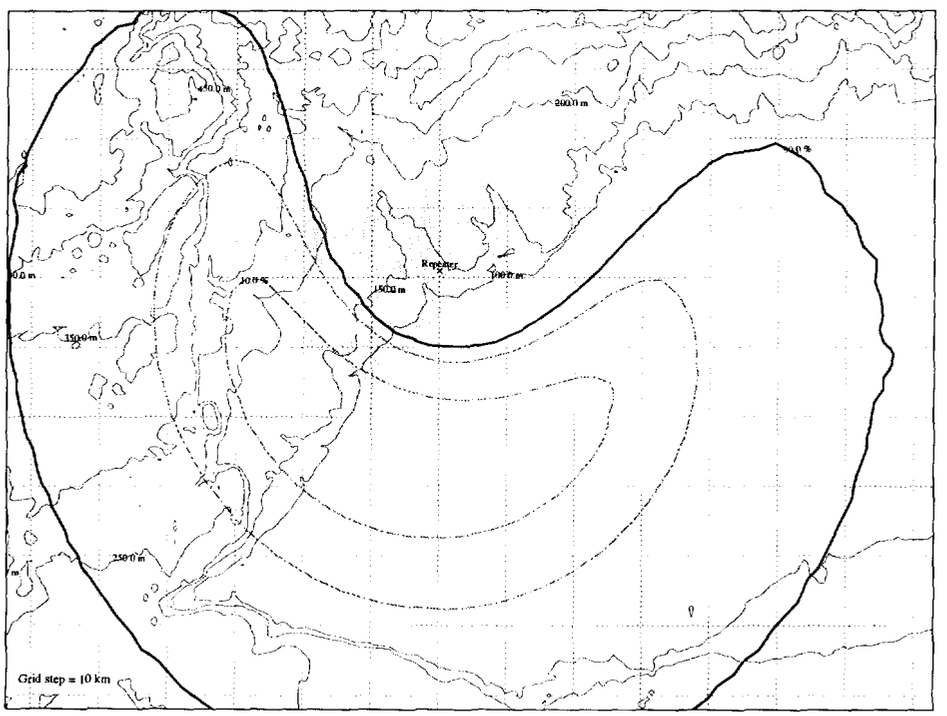

Figure 5.3: Hypothetical satellite DARS system with large interference area in the Toronto region due to excessive radiated power from the omnidirectional repeater.

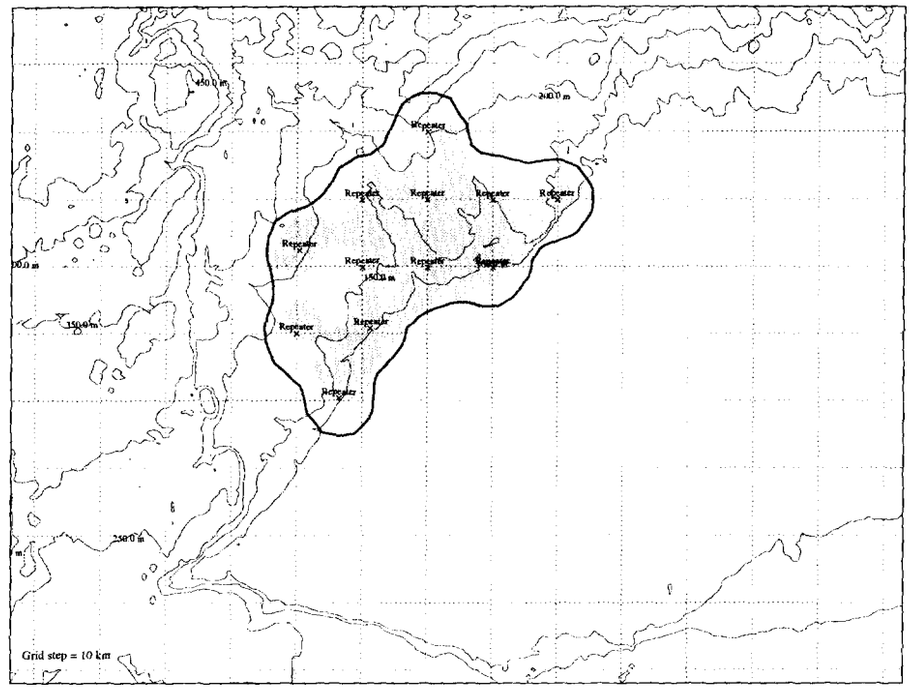

Figure 5.4: Hypothetical satellite DARS system with no interference area, using 12 well located low power omnidirectional repeaters.

Another elegant approach to avoid creating an interference area is to implement the repeaters using directional transmission antennas aimed away from the satellite and using medium power levels. This allows the use of higher power repeaters and still control the signal energy where the interference area would normally appear. Looking at the data from Table 5.2 and assuming a directional antenna with a 20 dB front-to-back ratio, the 4 W ERP limitation at 100 m EHAAT translates into 400 W ERP towards the downtown area. Although the antenna could easily provide better front-to-back ratio, this conservative value is needed in order to cover for possible back-scattering from buildings which would limit the isolation practically achievable in the field by the antenna. Such back-scattering would re-generate a local uncovered area, part of the crescent shape seen earlier in Figure 5.3, as if poorer front-to-back antenna rejection was experienced.

5.2.2 L-band and S-band coverage case study

So far, this coverage discussion was illustrative in order to explain the satellite/terrestrial interference phenomenon. A second example is now considered, this time based on a generic scenario to develop a comparison between what can be achieved at L-band and S-band. The target coverage area is a polygon of approximately 30 km by 50 km (i.e. representative of a coverage areas similar to metropolitan Toronto shown in Figure 5.2 and 5.3) and consisting of dense urban, urban, suburban, industrial and other types of areas.

Based on information provided in Section 3 of this report, it seems safe to assume that by using S-band frequencies instead of L-band frequencies, a penalty of typically 6 dB in satellite transmission power can be expected due to purely propagation and receiving antenna aperture considerations. Similarly, a 10 dB penalty is expected in the case of the terrestrial transmission for a 95% service availability.

Another important factor is the Doppler spreading of the signals due to vehicle displacement. Figure 5.5 presents computer simulation results showing the impact of Doppler spread in the worst case condition of a typical urban channel as defined in the COST 207 model [COS-89], seen as a degradation of system performance in E_b/N_o as a function of vehicle speed for Modes II and IV for a BER of 10^{-4}. The abscissa provides two different scales, one for L-band and one for S-band. This is based on the fact that Doppler spread is a linear function of both carrier frequency and vehicle speed. A multiplication factor of 0.63 (i.e. 1.472 GHz/2.335 GHz = 0.63) is used to scale the vehicle speed from L- to S-band. Environment types other than urban are not presented here because the urban environment will be the most critical as far as satellite signal outage, which is the reason why terrestrial on-channel repeaters are considered at all.

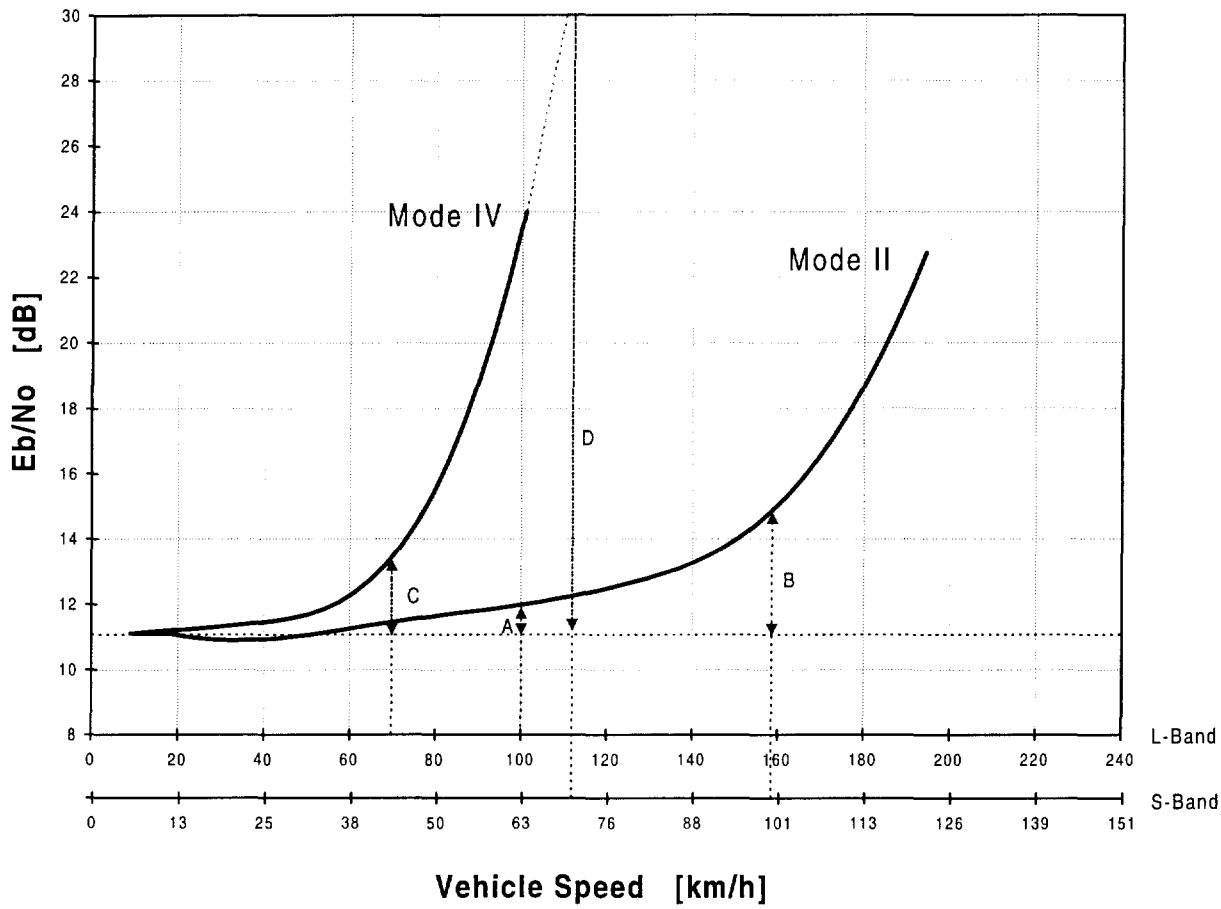

Figure 5.5: Impact of Doppler spread on Eureka 147 DAB system performance at a BER of 10^{-4} in Modes II and IV for the typical urban channel defined in COST 207, as a function of vehicle speed scaled for L- and S-bands.

Two scenarios will be developed here assuming a reference maximum vehicle speed of 70 km/h, in an urban environment, used for the purpose of comparison between L-band and S-band. This speed is used as a reference point for comparison purposes. As can be seen from Figure 5.5, 80 km/h is still comfortable as a maximum vehicle speed in Mode IV at 1.5 GHz for such an urban environment

It should be noted that for these two case studies, it was found more appropriate and accurate to use the Okumura-Hata urban propagation model which is based on extensive empirical data from measurements in urban environments, unlike in the illustrative case where the ITU-R PN. 370 propagation curves were used to model the suburban and rural propagation in the South-West area of

Toronto. This more realistic model has the merit of being based on measurements made in typical vehicular reception conditions and also being scaleable in frequency at L-band and S-band.

The first case study is an example of a L-band system using Mode IV with an impact of 2 dB on the terrestrial link budget due to spectrum spreading at a BER of 10^{-4}. The coverage of the hypothetical area of 30 km by 50 km for this system example is given in Figure 5.6 where, as can be found in Table 5.2, 250 W omnidirectional repeaters can be used for a EHAAT of 100m.

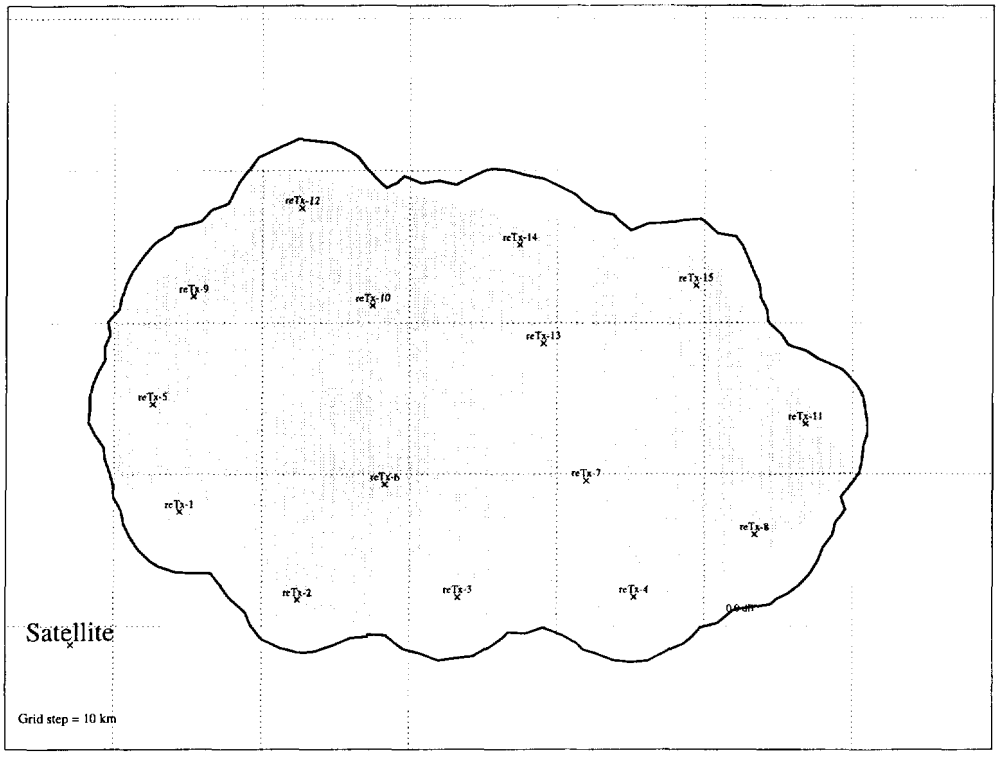

Figure 5.6: Service coverage of a predetermined area for L-band (Eureka 147 system in Mode IV) requiring 15 omnidirectional repeaters of 250 W ERP each at 100 m EHAAT.

These results are similar to those obtained in the Toronto case where 12 repeaters were required, using a different set of assumptions (Mode II, ITU-R PN. 370 model, 50 m EHAAT, etc.). Now, by applying a more refined system design approach, it is possible to substantially decrease the number of repeaters. Figure 5.7 shows the same situation but this time directional antennas are used yielding an equivalent coverage with only four (4) repeaters. This is explained by the fact that directional antennas with 20 dB front-to-back ratio potentially allow an increase of the ERP from the value indicated in Table 5.2 up to a value of 20 dB higher. In this case, the EHAAT was maintained at 100m but the ERP was increased to 12 kW which is 3 dB less than the maximum allowable ERP of 25 kW.

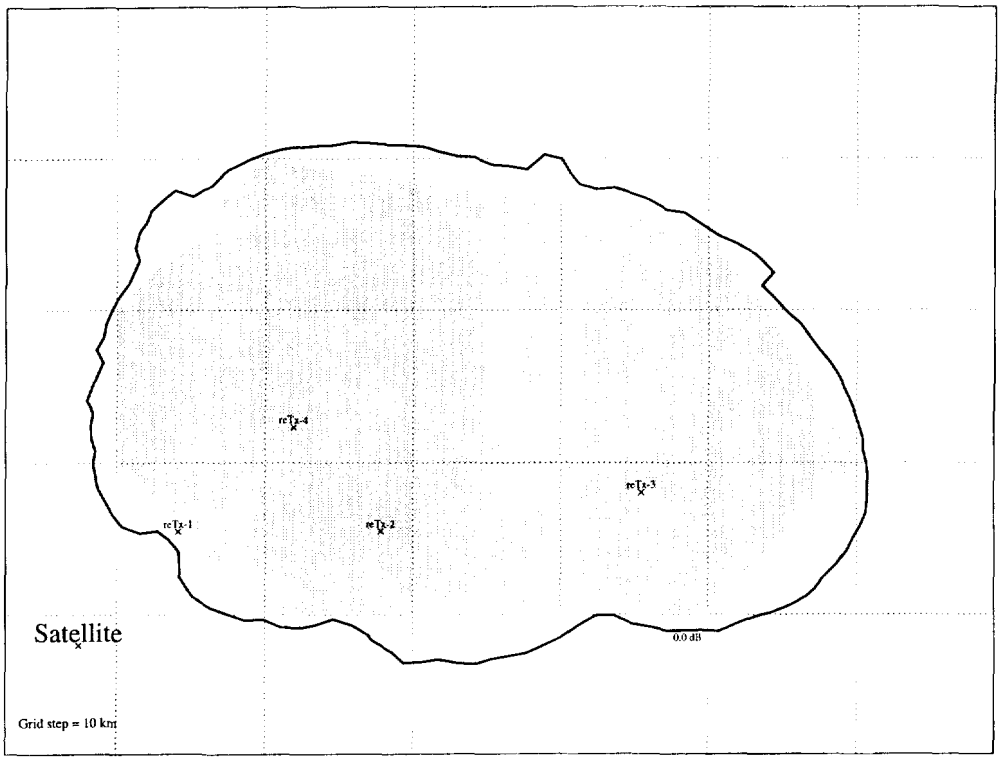

Figure 5.7: Service coverage of a predetermined area for L-band (Eureka 147 system in Mode IV) requiring 4 directional repeaters of 12 kW ERP each at 100 m EHAAT.

The second case study is at S-band. To be able to keep the same vehicle speed of 70 km/h, the symbol period and the guard interval (GI) duration need to be scaled down by a factor of 0.63 (relative to L-band in Mode IV) therefore reducing the guard interval from 123 µsec to 77.5 µsec. Mode IV could not be used in this case because the impact of Doppler spread on the terrestrial link budget would be too important: the vehicle speed would have to be limited to about 50 km/h to limit the impact on the required Eb/No to 4.5 dB as seen in Figure 5.5. At higher vehicle speeds, this impact would increase exponentially. Mode II could be used at S-band but, in order to be able to make a strict comparison between the two frequency bands, the proportional scaling of the guard interval was retained.

The maximum allowable ERP for 100 m EHAAT, at S-band, had to be interpolated from values in Table 5.2 between 4 W (GI = 62.5 µsec) and 250 W (GI = 123 µsec) for the scaled guard interval of 77.5 µsec needed at 2.3 GHz. This was done by first estimating the field strength at which the interference problem starts occurring for Mode II and Mode IV, at L-band. Figure 5.8 shows the field strength as a function of distance for three transmitters; two are at L-band and one is at S-band. The propagation model used here is the same as the one used to create Table 5.2 for 95% coverage availability. In Mode II, the interference zone starts at around twelve kilometers from the repeater, for a 30 degree elevation angle. Looking at the 4 W ERP curve on Figure 5.8, the corresponding field strength is 35 dBµV/m. In Mode IV, the interference zone starts at around 24 km. The 250 W ERP curve shows that for a level of 35 dBµV/m, the distance is indeed 24 km. The third curve was found using the same propagation model but scaled for a 2.3 GHz operation in a rural environment and the point of interest is the intersection of the 35 dBµV/m field strength with the distance of 15.2 km (i.e., 0.63 x 24 km = 15.2 km). The corresponding ERP value is what is considered to be the

maximum allowable ERP for an omnidirectional repeater at S-band to avoid satellite/terrestrial interference problem. This value is in the order of 20 W. Furthermore, the field strength at which the interference zone would start to appear would be 6 dB higher than in the 1.5 GHz case since the satellite transmission power has to be increased to compensate for the smaller receive antenna aperture and increased propagation losses as indicated in section 4.3.7. This being known, the simulations can then be performed using either 80 W omnidirectional repeaters or directional repeaters with an ERP of up to 8 kW.

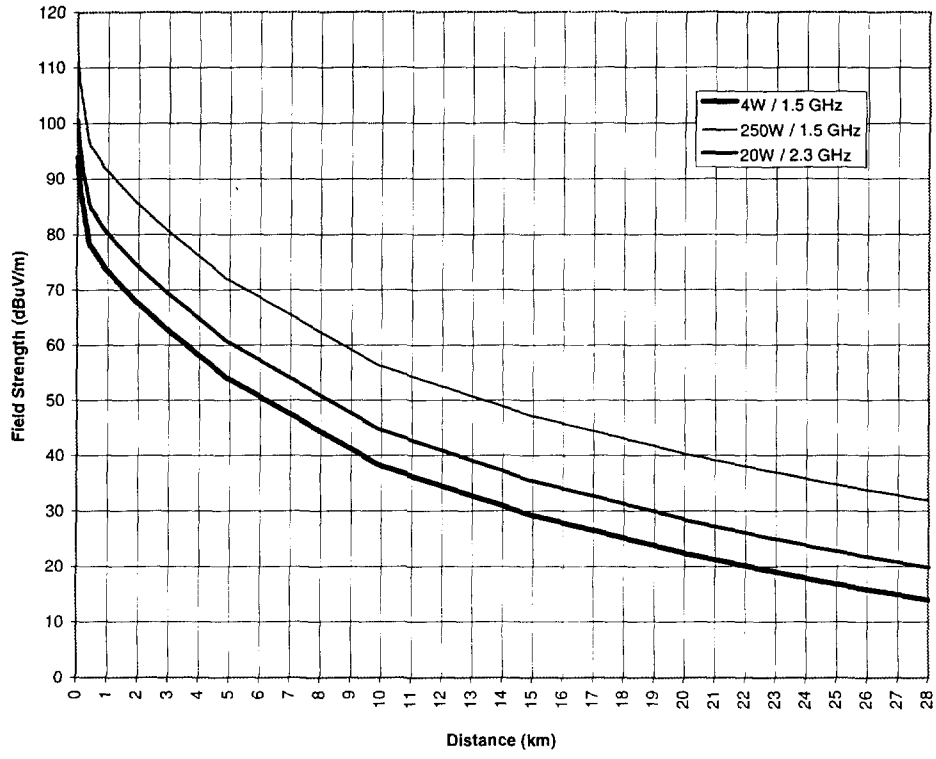

Figure 5.8: Field strength as a function of the distance from the repeater. Three ERP values are shown, 250 W and 4 W at L-band and 20 W at S-band.

At S-band, a penalty of 10 dB due to propagation effects for terrestrial transmission in urban environment, as explained in section 4.3.7, was taken into account in generating the coverage depicted in Figure 5.9. Eighty-five (85) repeaters are now necessary. The high density is mostly due to the propagation losses but another important limiting factor is the interference that the second and third row of transmitters causes to the first row, and so forth. This represents a considerable increase (by a factor of 5.7) in the complexity of the infrastructure, as well as the operations and maintenance costs, when compared to L-band.

Since the previous coverage exercise at L-band demonstrated the benefits of using directional antennas, a coverage exercise was repeated at S-band with repeaters equipped with directional antennas with 20 dB front-to-back ratio. This created a network of 9 directional repeaters operating at ERP of 8 kW, as shown in Figure 5.10.

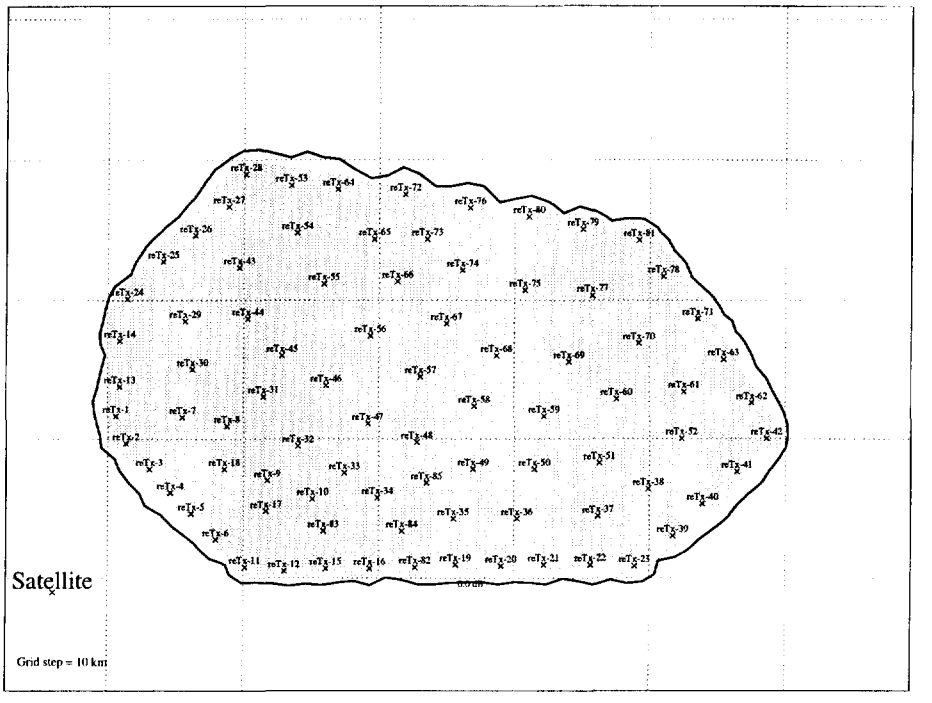

Figure 5.9: Service coverage of a predetermined area for S-band (Eureka 147 system) requiring 85 omnidirectional repeaters of 80 W ERP each at 100 m EHAAT.

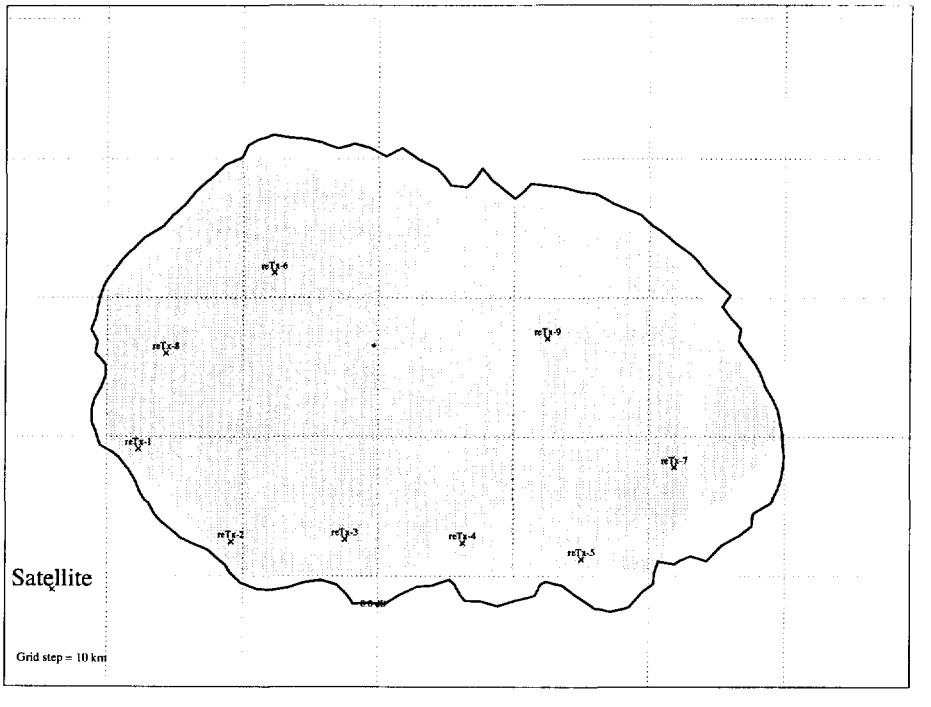

Fig. 5.10: Service coverage of a predetermined area for S-band Eureka-147 requiring 9 directional repeaters of 8 kW ERP each at 100 metres EHAAT.

These coverage simulations have illustrated the various extent of difficulty in implementing hybrid repeaters, whether in L-band or S-band. It appears clear that the S-band implementation is more difficult due to its large complexity shown by the number of repeaters required but, less evidently, by the difficulty in achieving proper coverage while controlling the effect of the multitude of destructive active echoes generated by this large number of repeaters

This comparison has been useful in determining a relative increase in the system complexity when using two different frequency bands. This was done by establishing a reference set of parameters which were scaled from L-band to S-band to minimize the number of variables that would affect the comparison. This should not be seen as an absolute answer to the presented theoretical coverage area (flat terrain with no blockage but still assuming the Okumura-Hata urban fading model). In an actual system implementation, the designers should be able to take advantage of the local terrain features and buildings to minimize the interference between repeaters and possibly reduce somewhat their required number. Never-the-less, the ratio in complexity between the two bands is likely to stay close to constant.

6. Single carrier modulation

Single carrier modulation is the other main candidate modulation for DAR systems required to operate in a hybrid satellite/terrestrial environment.

6.1 Proposed single carrier DARS systems

Of the four systems that have been proposed to the FCC to provide domestic DARS services via satellites in the US, three use a single carrier QPSK modulation. Those are the AMRC [AMR-92], Primosphere [PRI-92] and the CD Radio [CDR-92] systems. The fourth DARS system (DSBC) submitted to the FCC will not be considered here since it uses a transmission scheme based on spread spectrum techniques. The characteristics of the channel coding and modulation of these three systems are summarized in Table 6.1. Also shown in this table are the characteristics of the transmission schemes of two other systems that have been developed and proposed for DARS. The first one is the VOA/JPL system [ITU-95b] which has been submitted to and tested by the EIA/CEMA DAR Subcommittee [EIA-95] at 2 GHz. The second one is the WorldSpace system [SAC-97] which is to provide, at L-band (1452-1492 MHz), a satellite digital audio broadcast service to major parts of the world (Africa, the Middle East, Asia Pacific, Latin America and the Caribbean) by the next millennium.

Listed in Table 6.1 are the key parameters that affect the spectral and the power efficiency of the transmission. The information contained in this table is based on open sources and conversations with the proponents and reflects the best available information at this time. It should be emphasized that some of the parameters of this table are likely to change once the rules governing satellite DARS have been established and laboratory and/or field tests have been conducted. This is especially true for the two DARS systems to which spectrum has been auctioned by the FCC (AMRC and CD Radio). The VOA/JPL and WorldSpace are in an advanced state of development and have even been tested in hardware [EIA-95, SAC-97].

All of the systems listed in Table 6.1 proposed using QPSK (Quadrature Phase Shift Keying) modulation or its variant OQPSK (Offset QPSK). This choice is motivated by the fact that QPSK is a good compromise between spectral and power efficiency, the latter being a prime factor for satellite transmission. The other important consideration for QPSK is that this modulation provides