Study to Assess the Impact of Fade Mitigation Techniques in Bands Above Around 20GHz – Final Report

Produced for: Ofcom

Report No: 72/04/R/053/R
April 2004
Against Contract: AY4557 (510011210)
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<td>Draft</td>
<td>27-01-04</td>
<td>Draft Version for Review and Comment</td>
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<tr>
<td>Version 1</td>
<td>24-02-04</td>
<td>Project AY4557 Deliverable</td>
</tr>
<tr>
<td>Version 2</td>
<td>10-03-04</td>
<td>Project AY4557 Deliverable with missing references added and minor typos corrected</td>
</tr>
<tr>
<td>Version 3</td>
<td>12-03-04</td>
<td>Editorial updates for PDF version</td>
</tr>
<tr>
<td>Version 4</td>
<td>16-04-04</td>
<td>Editorial updates for publication</td>
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SUMMARY

This report contains the results of a study to investigate the potential benefits of applying Fade Mitigation Techniques (FMTs) to wireless systems operating in frequency bands above around 20 GHz and includes consideration of both terrestrial and satellite systems. The study consisted of three phases as follows;

- A Literature Search;
- Detailed analysis of four FMTs applied to specific scenarios as agreed with the RA;
- A Feasibility Study for a trial system based on one of the scenarios.

The Literature Search was undertaken to identify potential FMTs that are suitable for implementation within systems operating at frequencies above around 20GHz and to determine the status of either research or their deployment within existing systems.

For each scenario the detailed implementation, benefits (especially in terms of spectrum utilisation) and costs of incorporating a particular FMT were investigated. The main conclusion for each scenario was as follows;

- The use of Automatic Transmit Power Control (ATPC) in Terrestrial Pt-Pt systems can provide gains in spectrum utilisation due to a reduction in the required co-ordination distance;
- The use of Adaptive Coding and Modulation in a Terrestrial Pt-MPt (Mesh) Network provides significant gains in data throughput and/or the number of users supported by the network;
- The use of Site Diversity on the satellite uplink allows a reduction in the fade margin required to achieve a given outage probability, although in our particular scenario the implementation of the FMT was shown to be uneconomic;
- The use of Adaptive Antennas to compensate for stratiform rain fades is an interesting research concept but many years away from commercial realisation.

Finally, the feasibility study outlines a trial system that will generate measurement data to help Ofcom define a co-ordination policy for Terrestrial Pt-Pt radio links employing ATPC in bands where rain attenuation is the primary fading mechanism.
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1 ACKNOWLEDGEMENTS

The authors would like to acknowledge the following:

Ofcom (and the former Radiocommunications Agency) for funding the work detailed in this report and for their constructive comments and guidance throughout the project.

Antonio Martellucci (ESA) for providing a copy of the final report from ESTEC contract No. 12210/96/NL/SB(SC).

2 INTRODUCTION

This document is the final report of a study commissioned by the Radiocommunications Agency (RA), but whose duties have now been assumed by the Office for Communications (Ofcom), to assess the impact of Fade Mitigation Techniques (FMTs) in bands around and above 20 GHz. This work was carried out by Roke Manor Research (RMR), Rutherford Appleton Laboratory (RAL) and University of Portsmouth (UoP).

The objective of the study was to investigate the potential benefits of applying FMTs to wireless systems operating in frequency bands above around 20 GHz. This included both terrestrial and satellite systems.

The study consisted of three phases as follows;

- A Literature Search;
- Detailed analysis of four specific scenarios as agreed with the RA;
- A Feasibility Study for a trial system based on one of the specific scenarios.

The Literature Search was undertaken to identify potential FMTs that are suitable for implementation within systems operating at frequencies above around 20GHz and to determine the status of either research or their deployment within existing systems. The results of this Literature Search are provided in Chapter 3 with a list of references in Appendix A. It was found convenient to divide the FMTs into three main categories as follows:

1) Diversity Techniques;
2) Adaptive Techniques;
3) Signal Processing Techniques.

and the discussion in Chapter 3 is arranged on this basis.

Four specific scenarios were also identified and a ranked list of the FMTs that could potentially be applied to each scenario was produced. This is provided at the end of Chapter 3. From these lists one FMT per scenario was selected for detailed analysis as follows;
In each case a deployment scenario was defined and the benefits and costs of implementing the FMT within that scenario were investigated. Each analysis was structured in the following way:

- Scenario Definition (including implementation details);
- Assessment of the Performance and Spectrum Utilisation Gains;
- Cost/Benefit Analysis.

We have tried to adopt a common approach in our analysis of each scenario but significant differences between them mean that the nature of the benefits (and to a lesser extent the costs) of the four scenarios are very different. For example, in Scenario 1 the objective of the FMT is to increase spectrum utilisation as a result of reducing the separation distance between neighbouring links whereas in Scenario 2 the aim is to increase data throughput and/or the number of users that can be supported by the network.

In Scenario 1, given that most (if not all) of the currently available radio relay systems incorporate ATPC as a standard feature there is no longer any significant cost associated with deploying a new system. Benefits arise for individual operators due to operational cost savings but potentially also apply to the ‘industry’ as a whole in terms of an increase in spectrum utilisation due to reduced levels of interference.

In Scenario 2, the benefits outweigh the costs to such an extent that implementation of the FMT is fundamental to the commercialisation of the system operating in the 28 GHz frequency band. Conversely in Scenario 3 the costs outweigh the benefits to such an extent that no operator would implement the FMT within our particular scenario for commercial reasons. There are, however, other benefits that arise such as the opportunity to exploit higher frequency bands where employing Site Diversity on the uplink might be the only technically feasible way of achieving the required availability.

The approach taken for Scenario 4 was slightly different than the others as this was seen to be more of a future looking concept and therefore the analysis is less detailed but accompanied by a discussion of the advantages and disadvantages of the approach.

In Chapter 5 the results of an investigation into the feasibility of establishing a trial system to investigate the spectrum utilisation benefits of Scenario 1 is provided. It is expected that this will form the basis for the specification of such a trial system for deployment in the near future.

Finally, some conclusions are drawn in Chapter 6 with a list of references provided in Chapter 7 and a Glossary in Chapter 8.

### Table 2-1: Mapping of FMTs to Scenarios

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<th>Fade Mitigation Technique</th>
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<tr>
<td>1</td>
<td>Terrestrial Pt-Pt</td>
<td>Automatic Transmit Power Control</td>
</tr>
<tr>
<td>2</td>
<td>Terrestrial Pt-MPt</td>
<td>Adaptive Coding and Modulation</td>
</tr>
<tr>
<td>3</td>
<td>Satellite Pt-Pt</td>
<td>Site Diversity on Uplink</td>
</tr>
<tr>
<td>4</td>
<td>Satellite Pt-MPt</td>
<td>Adaptive Antennas</td>
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3 FADE MITIGATION TECHNIQUES (RESULTS OF LITERATURE SEARCH)

3.1 INTRODUCTION

Systems operating at frequencies above 10 GHz often experience severe fading due to rain events, which is unlikely to be compensated for by fade margin alone. As the demand for spectrum increases, more and more systems are moving up to these higher frequencies and so need to be capable of dealing with rain fading. This can be accomplished by the introduction of fade mitigation techniques (FMTs), which aim to compensate for the fade, while at the same time minimising the disruption to other services and misuse of system resources.

There are three main categories of FMTs, listed below:

1) Diversity Techniques.
2) Adaptive Techniques.
3) Signal Processing Techniques

Diversity techniques include time, frequency and spatial diversity, and mainly deal with the problem of a fade by moving around it. This can be done either in space, by sending the information on a different route to the one that’s being adversely affected, or similarly in the time or frequency domains; transmitting at a different time or in a different frequency band such that the probabilities of each signal being affected by a fade are statistically uncorrelated.

Adaptive techniques involve changing some aspect of the system set-up to compensate for the fade. For instance, in adaptive power control, the transmit power is increased to compensate for the effects of a fade.

Signal processing techniques work at the data layer, where the fade is compensated for by a more efficient coding or modulation scheme. In terms of spectrum efficiency, these keep the same basic amount of spectrum constant, and alter the rate at which the data is sent through that amount of bandwidth, in order to compensate for a fade. In situations where the data throughput must be kept constant, the amount of bandwidth used may be modified to compensate for a fade.

Finally, there are also hybrid FMTs which take aspects from all three categories, such as adaptive space time coding.

Figure 3-1 shows a block diagram of all the different FMTs identified over the course of the literature survey, and gives an indication as to where and how they all relate to each other.

Over the course of the review we have discovered a number of papers that have in turn performed their own review and literature survey. These tend to be more focussed in on specific services, e.g. slant path [Ref 78], [Ref 132] but go slightly deeper into the subject than this review will attempt.
There seems to be a general trend in that most of the papers on FMTs are biased towards the satellite services. This is because the fixed terrestrial services have, until recently, mainly been at lower frequencies where the effect of rain fades could be managed through the use of a suitable fade margin.

Techniques such as coding and adaptive TDMA [Ref 89], [Ref 63] could be designed to be more robust in the presence of fades, due to their built in error-checking facilities and the assignment of extra slots in the transmit frame to compensate for rain attenuation. CDMA is more robust against narrow band fades, because of the wider bandwidth involved. This has no impact on frequency planning, as the use of extra slots to compensate for rain attenuation means a reduction in the data throughput.
Figure 3-1: Block Diagram illustrating the different FMTs identified during the Literature Search
3.2 DIVERSITY TECHNIQUES

The basic principle behind diversity is the concept of routing the radio path around the source of the fading, whether this occurs in the space, time or frequency domains.

3.2.1 SPATIAL DIVERSITY

Rain is spatially and temporally intermittent and inhomogeneous. Intense rain cells that cause extreme attenuation on radio links often have horizontal dimensions of only a few kilometres. Spatial diversity takes advantage of this by routing the transmitted information along the path experiencing the least fading.

The performance gains achieved using spatial diversity are heavily dependent on the space and time correlation of rain fields, i.e. the distance that one has to have between two points before the behaviour of the rain at both points is completely uncorrelated. Hence there are a large number of studies focussing on the spatial and temporal variation of rain, including [Ref 82],[Ref 83],[Ref 67].

3.2.1.1 Route Diversity


Route diversity is generally used for terrestrial links involving either a mesh network or star topography. During a fade the system switches to the radio path experiencing the least amount of fading. Figure 3-2 shows a schematic diagram of a route diversity scheme.

System availability can be improved significantly, [Ref 136], given certain parameters including the length of the paths (\(L_1\) and \(L_2\)) and their angular separation (\(\theta\)). For example, for a system setup as shown in Figure 3-2, simulations using meteorological data show that for two paths of equal lengths and low separation angles (e.g. 30°) the diversity gain is between 0.9-1.5 dB and an improvement of 5%-40% from the original availability [Ref 136]. Star network diversity measurements carried out in Norway are presented in [Ref 135] and show diversity improvement factors within the range of 1.5-3 for a 10 dB fade and 2-4.5 for a 20 dB fade.

If a link is simply required to go from point A to point B, adding in extra routes is expensive and difficult to justify. The extra paths also take up geographical space, reducing the possibility for frequency re-use in a given area.
3.2.1.2 Site Diversity


Site diversity employs two or more ground stations receiving the same satellite signal with a separation distance usually greater than the diameter of the rain cells. The sites in a properly configured arrangement encounter intense rainfall at different times, and switching to the site experiencing the least fading improves system performance considerably. Figure 3-3 gives a schematic diagram of a typical site diversity scheme.

Site diversity as an FMT can be further subdivided into two categories: switched diversity and wide area diversity. Switched diversity involves one main receiving station and one standby station, which is switched to when the attenuation at the main station is too intense. Wide area diversity involves resource sharing between several earth stations interconnected using a terrestrial network [Ref 85].
Site diversity

Terrestrial link between earth stations

Earth station 1 experiencing fading

Earth station 2 experiencing no fading

Figure 3-3: Schematic Diagram of a Site Diversity Scheme.

Typical diversity gains achievable with this method at Ka band are between 10 dB and 30 dB, according to the distance between the base stations [Ref 107]. This method is particularly efficient for high availability systems, though the OPEX campaign has shown that the use of more than two stations does not significantly improve diversity gain [Ref 78]. This is contrasted by the paper written by Goldhirsh et al [Ref 99] which provides results from the three-site space diversity experiment at 20Ghz using ACTS, where fade margins of 9.4, 6.6 and 6.6 dB are required for each pair of the three sites to achieve continuous communications for 99.99% of the time, in comparison with the three-site fade margin of 5.1 dB.

Adding a second earth station into an earth-space network can be very expensive. Also, it is necessary to link the two earth stations via a terrestrial network in order to coordinate the switching, and so is suited for control stations and major gateways, but is too expensive for low cost VSAT or USAT without the use of public terrestrial networks.

3.2.1.3 Orbital Diversity


Orbital diversity allows the earth stations to pick between various satellites and use the one that permits the most favourable link with respect to propagation characteristics. Figure 3-4 shows a schematic diagram of orbital diversity. It is also used in constellation networks such as GPS and (the now defunct) Iridium to optimise the size of the constellation (i.e. the number of satellites) in order to limit the number of communications satellites at low elevations angles.
Experiments carried out in the past have demonstrated the possible use of orbital diversity as a FMT for future high frequency satellite telecommunications systems. Results at 12 GHz have shown that the diversity gain (both statistical and instantaneous) is higher for low-elevation links than for higher elevations links [Ref 73]. These results are expected to be improved at Ka-band frequencies.

The main disadvantage of orbital diversity is the cost of adding in different satellites to the network. In a constellation set-up, where there are a large number of satellites in play, this is more feasible.

For low attenuation, orbital diversity can provide gains if the clouds or rain motion are significant enough to successively disturb both links with a sufficient time delay. For high attenuation the diversity gain is high provided the attenuation on both links are not correlated. If they are correlated, then the gain will be low. It has been shown [Ref 124] that for geostationary satellites placed with small angular separation between them, the orbital diversity gain is related to the angular separation of the satellites.

**3.2.2 FREQUENCY DIVERSITY**


Frequency diversity is generally used for fixed satellite systems. If the normal transponder, which operates at higher frequencies is adversely affected by a fade, it is possible to switch to a transponder that operates at a lower frequency which is less sensitive to the cause of the fade. Carassa et. al., [Ref 75] give some frequency diversity results which are derived from the data collected at 11.6 GHz for the Sirio experiment. Dossi et al, [Ref 88] also state that frequency diversity is particularly effective when low levels of outage
probability are required and that very low levels of outage time cannot be achieved by means of other FMTs that directly improve the power margin, such as up-link power control.

This technique is relatively expensive, as it requires the user to have a dual frequency pair of terminals, one for each frequency as well as a double transmitter payload on the satellite. It makes it more complicated to share frequencies, both between users in the same system, and between different services. Frequency diversity is also very spectrum intensive. Correct implementation of the technique also calls for knowledge of frequency scaling characteristics and statistics (both long term and instantaneous) for the primary (higher) frequency and backup (lower) frequency.

### 3.2.3 Time Diversity

#### 3.2.3.1 Parallel Broadcast Streams


This FMT takes advantage of the temporal inhomogeneity of rain. If information such as a TV broadcast is transmitted several times with a delay between each transmission, then the receiver can accumulate the information from the times with the best receiving conditions. Figure 3-5 shows a schematic example of this FMT.

This FMT is particularly useful for broadcast applications such as live TV programmes with high audience numbers, for instance, football matches etc, where any break in service will not be tolerated by the viewers. The size of the delay between each of the transmissions can be tailored to best suit the prevailing weather conditions and time of day, also taking into account diurnal variations in attenuation levels. The availability of high capacity low-cost computer hard disk memory also assists in the implementation of this FMT. Studies have shown that for even small time delays such as 1 minute, system performance can be improved significantly [Ref 137]. Fukuchi et al, [Ref 96] present time diversity measurements made in Malaysia, while Ventouras et al, [Ref 137] present similar results for the UK climate.

The main disadvantage of this broadcast scheme is that it requires double the amount of spectrum to transmit both broadcasts in parallel than it does to transmit a single stream. This would limit its effectiveness as a spectrum conservation technique. Also, even with the current trend to reduction in price of high-capacity computer hard disk memory, the amount of memory required to implement this technique may be prohibitively large and expensive.
3.2.3.2 Selective Retransmission

References: Ventouras et al, 2001

Similarly to the parallel broadcasts technique, retransmission takes advantage of the temporal inhomogeneity of rain. However, it is more suited towards packet data applications, where if there is an unsuccessful delivery due to a fade, the systems repeats the transmission after a set time interval.

The statistics used to predict the gains from a selective retransmission scheme are the same as those used to predict the performance of a parallel broadcasts scheme [Ref 137]. Also, the selective retransmission scheme does not require the amount of bandwidth that the parallel broadcasts scheme needs.

To correctly implement this scheme requires a sensible method of coding the packet data in order to maximise the throughput. The receiving station also needs to be able to inform the transmitting station when a packet has not been received properly and to resend it.

Figure 3-5: Diagram of a Time Diversity Scheme, Parallel Broadcasts
3.3 ADAPTIVE TECHNIQUES

3.3.1 ADAPTIVE TDMA


Adaptive TDMA can be designed to be more robust in the presence of fades, because of the assignment of extra slots in the transmit frame to compensate for rain attenuation. This has no impact on frequency planning, as the use of extra slots to compensate for rain attenuation means a reduction in the data throughput.

Campora ([Ref 69], [Ref 70]) presents results for resource sharing in satellite downlinks operating at 12 GHz, using resource sharing of a small pool of reserved time slots in a TDMA frame. For a maximum resource sharing gain of 10dB, results are presented that show that reserving six percent of the time slots ensures a realized fade gain in excess of 9dB, for a downlink outage objective of 0.005%, if there are more than 50 ground stations in the network, each with 2% or less of the traffic.

3.3.2 ADAPTIVE POWER CONTROL

3.3.2.1 Uplink/Downlink Power Control


Power control is used with earth-space links, though it could be also applied to terrestrial links. It involves increasing the transmit power in order to be able to compensate for fades.

Given a reliable power control system, it could be possible to reduce the fixed fade margin during clear sky conditions (i.e. no fading), thereby improving the rate of frequency reuse in the geographical area of the link. This is because lower fade margins mean less transmit power, which lessens the interference on adjacent links.

Dissanayake [Ref 84] presents results from an experiment conducted using the ACTS satellite to evaluate the efficacy of open-loop uplink power control. The open loop scheme relies on estimating the uplink fade by an independent means, such as radiometry or monitoring the satellite beacon. In closed-loop implementations, the transmitting station uses its own transpond carrier to estimate the uplink fade. The investigation was limited to a power control range of 18dB, 15dB of fading and 3 dB of enhancement. The aim was to maintain the power flux received at the satellite at a constant level, irrespective of the fading along the radio path. It was found that in most conditions the power control accuracy could be maintained within ±2.5 dB.

A disadvantage of uplink power control is that during unfaded conditions, the quality of the up-link will be worse than that of the fixed power scheme for the same maximum power output by the dynamic range of the power scheme. The down-link is unaffected as a new transponder operating point may be chosen to compensate for reduced up-link power. The total link quality is reduced by the reduction in uplink or downlink quality, and thereby decreases the systems tolerance to fading. There is a trade-off between uplink and downlink fade tolerance, due to the link balance [Ref 91] which means the link must be carefully
defined [Ref 139]. It is considered sensible to have the same availability on both up-link and down-link, though for services such as DVB-RCS and video-on-demand this may not be necessary.

There are also potential problems associated with the stability of this technique, as it involves increasing transmit power, with the implication that if there is no fade present, the resulting increase could adversely interfere with other neighbouring systems. Potential misuse could result in a feedback loop where two or more systems interfere with each other, each increasing their transmit power to compensate, and thereby interfering with the other system even more.

### 3.3.3 Adaptive Antennas/Beam-shaping


This technique is based on the flexibility of adaptive antennas, whereby spot beams can be adapted to propagation conditions in a specific ground area [Ref 127]. This is done by adjusting the satellite antenna gain by reducing the size of the spot beam in the affected region, thereby compensating for rain only in the areas where it's likely to occur.

The results obtained are similar to those achieved using up-link/down-link power control, but without increasing the transmit power, thereby reducing the risk of increased interference. The system can also be used to more efficiently target the distribution of users in the coverage area. Kalatizadeh et al, [Ref 108] have shown that if a reconfigurable antenna system is employed, much higher flux densities can be achieved by modifying the antenna pattern to redirect the power to the high attenuation areas. Even with allowing for the 1-2dB loss in the variable power divider and phase shifters needed, the improvement in the minimum flux density at 0.1% outage is 2-3 dB, justifying the additional cost.

However, if the size of the beams are reduced this means that more beams are required to cover the same geographical area, resulting in changes in frequency planning and interference issues. In terms of spectral efficiency, this technique is spectrally more efficient, but comes at the cost of added complexity due to the need to dynamically manage the spot beams.

With this FMT, the characteristics of the fade as it occurs is not as important as with other FMTs. However, the meteorological conditions on the ground are of great importance, and short-term weather prediction (also known as "nowcasting") is required to determine the orientation and velocity of the rain cells and fronts. The cost of the adaptive antennas is also high in comparison with other methods.

### 3.3.4 Adaptive Modulation


The aim of the adaptive modulation technique is to change the required bit energy to noise ratio corresponding to a given BER (bit error ratio) by reducing/increasing the spectral efficiency as the carrier to noise ratio decreases/increases. This means that during a fade the modulation scheme is changed so as to allow more of the data to get through, or in cases where the bandwidth is constrained, the data throughput is reduced. As the carrier to noise ratio increases, the spectral efficiency improves.
Using modulation schemes with high spectral efficiency can result in higher system capacity for a specified bandwidth. This makes it possible to transmit more bits per second without increasing the bandwidth proportionally. The disadvantage of using higher order modulations is that their susceptibility to noise is increased.

Working on the assumption that the system wishes to maximise the data throughput for a given constant bandwidth, then this technique, along with adaptive coding, is bandwidth neutral. Therefore its use as an FMT does not have the potential of reducing the amount of bandwidth used by the system during non fading conditions, as the system will automatically seek to use the most efficient method of modulation at all times. However, in situations where the data rate is constant, then adaptive modulation can reduce the amount of bandwidth needed during clear sky conditions, resulting in a gain in spectral efficiency. This is discussed in Bolla et al [Ref 65].

### 3.4 SIGNAL PROCESSING TECHNIQUES

Most signal processing techniques seek to deal with the problems caused by the physical layer, i.e. fades, by the addition or modification of coding, which happens at the data layer of the system. For this reason, the codes used tend to be very system dependent, as they rely on the hardware and software already in place.

The basic principle of coding is adding redundant bits to the information bits; the redundant bits will then be used at the receiver to detect and correct errors. Two types of coding are commonly used: block coding and convolutional coding. Cyclic codes, for which every code word is a multiple of a generating polynomial, are also used. Reed-Solomon and BCH (Bose, Chaudhari and Hocquenghem) are the most commonly used block codes.

Although coding can be used to reduce error rates, it can be convenient to think in terms of the increase in power that would be needed to deliver the same performance in an uncoded system. This quantity is called the coding gain. There are difficulties arising from this concept in comparing like with like, because one effect of adding coding to a channel is the reduction of the information transmission rate due to the addition of redundant bits to assist with error correction. This difficulty is overcome by assessing error rates against the ratio of energy per information bit to noise power spectral density \(E_b/N_0\). The effect of this is to penalise the coded system by \(10 \log_{10}(1/R)\) dB, where \(R\) is the coding rate. For example, a code with rate \(\frac{1}{2}\) shows a 3dB increase in \(E_b/N_0\) prior to decoding, compared with an uncoded channel.

Since we hope that the uncoded channel will work at lower power, the reduced error rates given by the coding must at least compensate for that 3dB penalty if any coding gain is to be seen at all [Ref 91].

#### 3.4.1 DATA RATE REDUCTION


Unlike power control, which aims at restoring the carrier to noise ratio during a fade by increasing the transmit power, data rate reduction allows the system to cope with the decreased carrier to noise ratio experienced during a fade while maintaining the link performance in terms of BER (bit error ratio). Data rate reduction aims to decrease the information data rate at a constant BER. This is in comparison with
adaptive coding and adaptive modulation, which allows the system to reduce the required energy per information bit level.

Keeping the transmitted data rate constant and varying the information data rate means that the systems can operate at a constant resource level. User data rates are matched to the propagation conditions, where there is no fading then normal data rates are used. When fading occurs, the data rate is altered according to fading levels.

This FMT, which is based on the principle of fade spreading, has been tested within the DICE videoconference experiment [Ref 114]. The concept of the experiment was to operate at constant satellite resource allocation per user (burst length, bandwidth) through a constant transmitted data rate. This FMT can only be applied to services that can tolerate a significant reduction of the information rate. This makes it a possibility for services such as video and data transmission, but is impractical for voice transmissions.

3.4.2 **Forward Error Correction**


There are various methods available for decoding the block and convolutional codes used in slant path systems. With block cyclic codes, one of these methods uses the calculation and processing of syndromes resulting from the division of the received block by the generating polynomial. If this result is zero, then the transmission is error free.

Forward error correction introduces redundancy to combat transmission errors. These coding schemes can be used as FMTs if the capacity of the radio link is permitted to decrease during a fade. During a fade the information data rate is reduced and extra coding information is inserted into the channel so that the channel rate remains constant.

The coding scheme realises a net gain of typically 2-10dB depending on the coding rate [Ref 139]. This comes at the cost of an increase in the required bandwidth. Lu and Brodersen [Ref 119] discuss forward error control in the context of a CDMA downlink system.

To ensure maximum efficiency, it is possible to use a separate optimised code for each rate. These variable rate coding schemes tend to be expensive. This form of coding can only be used for services that can tolerate a reduced throughput when faded, e.g., data transmission. It is not suitable for real time applications such as voice transmission/video conferencing etc.

3.4.3 **Adaptive Data Rate/ Coding**


Adaptive data rate/coding is commonly used in systems which already operate with a high level of coding at the data layer, for example GSM EGPRS. During a fade the coding scheme can be altered to introduce more redundant bits, to allow the receiver a better chance of correcting any errors. The same information data rate can be kept as in clear sky conditions, however this comes at the expense of a greater bandwidth. Most systems tend to keep their bandwidth constant and alter the rate at which the information bits are sent along the link, in order to allow for the extra errors introduced by fading.
This FMT is comparatively easy to implement, as systems already use block and convolutional codes in order to efficiently transmit data. However, similarly to adaptive modulation, this FMT is bandwidth neutral.

3.5 HYBRID TECHNIQUES

3.5.1 ADAPTIVE SPACE-TIME CODING

References: Bevan and Tanner, 1999, Frigyes and Horváth, 2003

Combining the concept of diversity and coding enables the system to transmit an appropriately coded signal stream across a number of routes, instead of transmitting the same signals over the diversity routes independently of each other. Space-time codes operate by taking the input stream of information bits and generating vector outputs of simultaneous transmissions from a number of different transmitters spread out in space. These vector transmissions are known as space-time-symbols.

Frigyes and Horvath [Ref 95] state that space-time coding schemes promise enhanced performance in terms of power efficiency, and spectral efficiency, i.e. they have good error performance at low signal to noise ratios.

The effectiveness of coding schemes is fundamentally limited by the fact that the maximum channel efficiency cannot exceed the Shannon limit, $E_b / N_0 = \frac{1}{\log_2 e} = -1.6$dB (where $E_b/N_0$ is the bit energy to noise ratio) Although it is theoretically possible to operate a link at this limit, in practice available demodulators limit the minimum channel $E_b/N_0$ to around 0dB. Below this, the demodulator may not be able to sample correctly as it may not be able to recover a reliable bit timing clock.

3.5.2 FORWARD ERROR CORRECTION WITH AUTOMATIC REPEAT REQUEST


Forward error correction is a type of coding that usually extends the transmission bandwidth needed to convey a given data rate, but substantially reduces the power needed to support the communications link. FEC with automatic repeat request is discussed in Koyabe and Fairhurst [Ref 118] in the context of the performance of reliable multicast protocols via satellite. The authors evaluate and analyse (using simulation) the performance of reliable multicast techniques over satellite topologies that are experiencing persistent fades, and are linked to a larger group of receivers. They show that for large receiver groups the control information from the receivers using the FMT incurs unnecessary delay because of link access delay. This technique could gain better performance if both the source and receivers had adequate information regarding the condition of the link before transmitting the data. Once again, use of this technique is bandwidth neutral as the data rate is changes while keeping the bandwidth constant.

3.5.3 ADAPTIVE DATA RATE WITH UP POWER CONTROL

References: Celandroni et al, 1996
Celandroni et al. [Ref 81] describe a modem that is able to change the transmit power and the bit and coding rates on a sub-burst basis. Their results apply to a simulated centralised and distributed control TDMA access scheme and show that for a reference level at the receiver input of $E_b / N_0 = 12$ dB, un-coded data has a BER of $10^{-8}$. Using coding, this BER can be maintained for $E_b / N_0$ that drops to 6 dB. By reducing the data rate from 8 to 1 Mbits/s a further gain of 9 dB can be obtained. Along with 10 dB of up power control, this gives a total 25 dB span for all the FMTs considered working together.

This technique is relatively inexpensive, but needs to detect the fade in the signal quickly and accurately, perhaps requiring some form of short-term prediction of the signal levels.

### 3.6 Ranking of FMTs

Table 3-1 shows the rankings of the proposed FMTs in their application to each of the four proposed scenarios. These rankings are based on simplicity, implementation risk and minimization of the impact on other users of the same service, as well as other services operating in the same frequency band. A few FMTs were deemed to be not applicable to any of the proposed scenarios, for instance orbital diversity, as none of the scenarios use more than one satellite. Parallel broadcasts and adaptive space-time coding were also not appropriate for any of the scenarios.

Most of the FMTs proposed in the literature are designed with earth-space services in mind. This is because most terrestrial services operate at frequencies where rain fades can be compensated for by a sufficient fade margin. However, some FMTs designed for satellite services can be adapted to terrestrial services, for example the concept of spatial diversity being split up into site diversity for satellite systems and route diversity for terrestrial systems. ATPC is another FMT that can be applied to all of the proposed scenarios.

Typically, the FMTs require extra cost to implement, whether in terms of additional hardware (such as a more complicated transmitter for adaptive antennas) and/or software (such as the procedures for adaptive coding in the data layer of the system). There is also usually a trade-off between data throughput and spectral efficiency. FMTs are also affected by the switching delay, that is the time between when a fade is detected and when the technique is applied, during which changes in the weather can cause unexpected outage or false alarm states.

The FMTs underlined for each of the scenarios in Table 3-1 were those chosen by the RA for further investigation.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario Constraints</th>
<th>Applicable FMTs ( Ranked)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial Point-to-Point</td>
<td>Users require constant data rates</td>
<td>1. Power Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Adaptive Coding &amp; Modulation (with variable bandwidth)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Frequency diversity</td>
</tr>
<tr>
<td>Terrestrial Point-to-Multipoint</td>
<td>Range of services considered: eg speech, internet, video, etc.</td>
<td>1. Power Control</td>
</tr>
<tr>
<td>(Mesh Network)</td>
<td></td>
<td>2. Adaptive Coding &amp; Modulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Time diversity (for non-real time services)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Forward Error Correction with Automatic Repeat Request</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Route Diversity</td>
</tr>
<tr>
<td>Satellite Point-to-Point</td>
<td>Variable rate, low bandwidth data service</td>
<td>1. Uplink Power Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Site Diversity on Uplink</td>
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<tr>
<td></td>
<td></td>
<td>3. Adaptive Coding &amp; Modulation on Downlink</td>
</tr>
<tr>
<td>Satellite Point-to-Multipoint</td>
<td>Variable rate data service</td>
<td>1. Uplink Power Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Adaptive Coding &amp; PSK Modulation. (Implicit frequency diversity due to system usage of MF-TDMA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Forward Error Correction with Automatic Repeat Request</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Time Diversity: Selective Retransmission</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Adaptive Antennas</td>
</tr>
</tbody>
</table>

Table 3-1: Ranking of FMTs for Each Scenario