Radio Systems at 60GHz and Above

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SUMMARY

Introduction

This is the final report for a study for OFCOM to investigate the current state and future bands above 60 GHz in terms of devices, systems, applications, sharing and regulations.

The utilisation of spectrum is leading to the need to consider higher frequency communication systems, including those in the millimetre-wave band. Greater use of the bands above 60 GHz could provide a useful increase in the spectrum available and could also release spectrum at lower frequencies for other purposes. The 60 GHz band, in particular, is well suited as it combines the potential for large information bandwidths with highly efficient frequency reuse due to the natural isolation offered by the oxygen absorption band. This makes it possible to reuse the same spectrum enabling closely spaced adjacent systems. However, as these frequency bands suffer severely from rain attenuation, their usefulness on their own for outdoor systems may be limited.

Applications that have been considered for these bands are short fixed links, high data rate links between buildings, broadband last mile applications, aircraft links, indoor WLAN, telematics (e.g. vehicle-to-vehicle, advanced vehicle control, co-operative driving, vehicle to roadside and safety systems), personal broadband applications, etc. An attraction of exploiting these high frequencies is not only the potential availability of high bandwidth systems but also the availability of small scale technology that could be used to reduce size and weight of the applications developed.

This study was decomposed into two threads.

- **Theoretical studies and literature searches**
  
  The major goal was to map out the current state and future of bands above 60 GHz in terms of devices, systems, applications, sharing and regulation.

- **Operation of real systems**
  
  A commercial system using the 60GHz band was operated in an industrial environment in conjunction with a FSO (Free Space Optical) link.

  In addition several years’ of frequency diverse experimental data (at 57, 97, 135, and 210 GHz and data from a FSO link) was analysed to provide base-line operational data. The data collected on the 500 m range at Chilbolton, UK during the period April 1991 to September 1995
**Objectives**

The scope of the work covered was to investigate the following topics:

1) *Examination of System Applications in the Bands 60-100GHz*

A number of typical applications for millimetre wave communications systems have been examined and their performance evaluated in adverse weather conditions (rain, fog and turbulence), where applicable. These applications included:

- Line of sight point to point links (LOS)
- Free space optical systems (FSO) (for comparison)
- Giga bit/s Wireless LAN
- Broadband fixed wireless access (BFWA)
- Satellite communications (Satcom)
- Aero satellite communications (Aerosat)
- High altitude platform systems (HAPS)
- Mobile systems
- Short range repeaters for network backhaul
- Personal communications
- Home communications

2) *Identification of key obstacles to band use*

Study into device technologies at millimetre and sub-millimetre wavelengths, particularly for airborne and space based applications. Unlike lower frequencies, semiconductor integrated circuits do not provide the complete answer at millimetre waves. Significant amount of the product size and cost consists of passive components based on waveguide structures, used for implementing and enclosing filters, diplexers, gain stages and interconnects. This complex of plumbing must be replaced by a technology that can scale down in cost as market size and applications expand. The radio link must evolve in cost effectiveness in a manner similar to the cellular phone, the PC and digital cameras. New architectures must be developed with a low-cost appliance-design mindset.

3) *Implications of Licensed and Licensed-Exempt Use & A survey of International Activity in Bands 60-100 GHz*

An international survey has been conducted into regulation, systems and applications of frequency bands specified by the ITU-R for telecommunications use. The objective of the survey was to determine how the higher frequency bands would be utilised in various licensing scenarios (e.g. no, light touch and fully managed licensing). In support of this, national regulators, voluntary standardisation bodies and commercial organisations have been approached. The main bands of interest internationally are 60-61, 64-66, and 71-76/81-86 GHz.
4) Radio Channel Characterisation

Channel sounders are used to evaluate the typical delay spread in a range of environments where high frequency wireless connections may be used e.g. mobile telecoms and WLAN applications. The distribution of delays is determined by the multi-path scattering environment e.g. reflections off the ground, buildings and internal walls within buildings.

Durham University have developed radio channel sounders based upon FMCW techniques. Data processing algorithms have also been developed to extract information about the channel from the measured data. The work to date has been addressing frequencies up to 6GHz.

This work package included the provision of the frequency extension modules for the existing channel sounder, integration and calibration of the sounder at the new bands, channel measurements in a variety of configurations and manipulation of data to provide results.

A series of measurements were made characterising typical indoor-indoor and outdoor-indoor propagation paths. Measurements were made using a range of commercial and academic buildings, built of a range of materials, and being put to a range of uses. Limited outdoor mobile measurements around the campus of the University were also carried out.

5) The spectrum Efficiency of Frequency/Power Control

Examination of rain scatter and ATPC for heterogeneous networks using sophisticated rain scatter and rain field models

Adaptive Transmit Power Control (ATPC) has been proposed in the literature as a promising technique for opening up higher frequencies to commercial exploitation. It can also be used at lower frequencies to reduce the transmit power used during clear sky conditions and compensating for fading on a dB by dB basis. This would enable an increase in the rate of frequency re-use, and hence an improved spectral efficiency.

Radio systems operating at 60GHz and above are not currently efficient or economical due to the large fade margins required to compensate for the intermittent yet dramatic effects of rain fading. ATPC and Dynamic Frequency Diversity (DFD), are fade mitigation techniques which can help to make systems at these frequencies more economical, and hence more open to commercial exploitation.

6) Dual Millimetre Wave/FSO systems.

Frequency bands above 60 GHz suffer severely from rain attenuation. This will put constraints upon the length or availability of links. Free Space Optical (FSO) systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However, it is speculated that heavy rain and fog/mist rarely occur
simultaneously. Therefore, frequency diverse systems, combining mm-wave and Free Space Optical (FSO) systems, have the potential to provide very high availability with reduced interference. The joint statistics of operation of the mm-wave link in combination with the FSO link were studied.

**Demonstration and Operational Trials of Working systems**

The purpose of the Demonstration and Operational Trial was to verify the availability, reliability and performance of millimetre-wave radio equipment in routine production and to consider its economic viability deployed in a commercial environment. For comparative purposes, an FSO link equipment was also deployed in a dual configuration on a parallel path. OciusB2 hosted the trial at their site in Runcorn, Cheshire; the equipment was commissioned to provide links between the main site and a business park at The Heath. OciusB2 transmitted commercial traffic across both the 64GHz link and the FSO link. Installation and deployment were completed by March 2005 and the operational performance of the links was continuously monitored for system parameter errors and failures through to November 2005.

The trial also enabled a typical set of deployment costings to be generated, and dual mm-wave/FSO link to be bench-marked against other technologies and deployment options for short-range high data applications.

**Conclusions and Recommendations**

The following conclusions were drawn:

**Examination of System Applications in the Bands 60-100 GHz & Identification of Key Obstacles to Band Use**

Millimetre wave communications systems at frequencies above 60 GHz have the potential for very high capacities, especially as more than 10 GHz of bandwidth is available in the current frequency allocations.

Spectrum that is not subject to the oxygen absorption effect exhibits behaviour which is broadly similar to spectrum below 60GHz where, in the absence of precipitation fading, the limit of propagation is the horizon.

Specific applications have been identified that require broad contiguous blocks of spectrum e.g. radio transmission of gigabit ethernet services.

Millimetre wave communications applications need to operate over short paths (< 10km) and also need to take advantage of the high antenna gains and directivities, which can be achieved with small antenna sizes (typically 10 < diameter < 30cms).
Two applications have been identified for further study. These are:

- a. Wireless local area networks providing ~1Gbps capacity through millimetre wave access points.
- b. Very high capacity backhaul for either MESH or branch and tree networks, operated in conjunction with very local wireless distribution services at lower frequencies.

The exploitation of these bands requires the development of low-cost RF technology.

At the frequency range 60 – 100 GHz transmitter/receiver technology is reasonably mature and mass-produced systems are commercially available. For example transmitters with 10mW output power and receivers with 10dB Noise Figure are available today to fulfil the radio link requirements for the applications presented in section 2.

Millimetre wave systems are not particularly suited to situations where long range is required e.g. satellite or HAPS systems or where non-line of sight paths are experienced (e.g. personal communications and home networks).

Millimetre wave systems, at ranges of more than 100m, provide a much better quality of service, in adverse weather conditions (rain and fog), than free space optical (infra red) systems.

Implications of Licensed and Licence-Exempt Use & A survey of International Activity in Bands 60-100 GHz

Manufacturers are now launching useable product, especially near the oxygen peak at 60GHz. These products exploit USA-FCC rules and provide a range of typically 1km. There is also some activity at higher frequencies with longer range but manufacturers are waiting for orders before committing to production tooling.

European and other regulators are starting to respond, although the response is far from uniform, e.g. between Europe, USA, and ROW. Within Europe some regulators are establishing national regimes, but most have waited for the report of SE-19. There is still a preponderance of formal licensing, but some regulators will adopt a mix of unlicensed and lightly licensed processes.

The bands 59-66 GHz : 71-76 GHz : 81-86 GHz should be opened on a lightly licensed basis so as to satisfy growing demand.

‘Light licensing’ should be adopted. Traditional spectrum auctions have resulted in the bands at 3.5GHz, 10.5GHz and 28GHz being privately owned but not deployed, and no-one from manufacturing or operating industry has made a case for using the same failed mechanisms in the new bands. Nevertheless, QoS requirements for the identified applications require a degree of interference management. This could best be achieved by following the new USA, low-cost, web-based registration scheme.
Due to the nature of the applications and the directivity of operational equipment in this band, there should be no restriction on channel size. 10GB/s radio links would require the full 5GHz spectrum.

In order to obtain the QoS required for the delivery of the identified applications, the power levels given in tables A4.2 and A4.3 of the Draft ECC Document ECC/REC/(05)07 ‘Radio Frequency Channel Arrangements for Fixed Service System’ should be increased. Suitable limits for power at the antenna port for 1Gb in both the 71-76GHz and 81-86GHz bands are 19dBm for FSK links, and 16QAM links.

There should be no modulation requirements or restrictions. It is believed that BPSK/QPSK will be used in the majority of links due to the link length requirements

TPC should not be mandatory.

Ofcom should maintain an ongoing interest in the development of a Europe-wide regulatory regime in the frequency bands between 60 and 100GHz that is sympathetic to the needs of both operators and manufacturers; and that the development of both regulations and market be continuously monitored throughout 2006.

Radio Channel Characterisation

Subject to the use of appropriate directional antennae line of sight paths operated with low levels of multi-path components both in building and out of building.

Operation through glass was demonstrated with little degradation in multi-path behaviour particularly for near normal incidence. Some smooth frequency selective behaviour was observable across the frequency band measured.

Non line of sight propagation was observed to result in a wide spread of delay components of near equal amplitude within a single corridor.

Non line of sight propagation around an obstacle was observed to occur at discreet frequencies across the band measured only. At other frequencies transmission was attenuated.

For outdoor links the strong reflection from adjacent structures must be considered when selecting the antennae and the location of the terminal equipment.

The spectrum Efficiency of Frequency/Power Control & Dual Millimetre Wave/FSO systems

Previous studies have investigated the spectrum efficiency benefits of implementing ATPC in bands up to 38 GHz, primarily concentrating on fixed terrestrial links. In higher frequency bands the situation is complicated by the 10GHz band around 60 GHz, where the oxygen absorption band suppresses long distance transmissions, hence
enabling a reduction of the frequency reuse distance to as little as 1 km in some situations.

The link layout scenario presented in this report is by necessity simplistic, dealing as it does with only two links and a simplified rain model. Still the results suggest that ATPC has the potential to improve spectrum efficiency in bands above 60GHz. As a worse W/U is predicted in clear sky than in rain, designing a link to clear sky specifications and compensating for rain fading dynamically on a dB by dB basis will minimise the separation distance between the links.

Frequency bands above 60GHz suffer severely from rain. (Frequencies around 60GHz suffer also from oxygen attenuation which in contrast with rain attenuation is always present). Free Space Optical (FSO) systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However the study of the joint statistics between a microwave and optical link indicates that the deep fading at the two frequencies did not occur simultaneously. This verifies the potential significant increase in availability possible with the dual frequency configuration.

From measurements made at Chilbolton on the 500m range to achieve an availability of 99.99% on a FSO link, a fade margin of over 40 dB is required. For a radio link at 57 GHz, a fade margin of ~10 dB would be needed for the same availability. A combined system using both a FSO link and a radio link at 57 GHz would require a 2 dB fade margin on the radio link and a 10 dB fade margin for the FSO link, which is a substantial reduction.

As with ATPC, reducing the transmit power of a radio link during clear sky conditions will improve the rate of frequency reuse within a given geographical area. At this time, effective and economic utilisation of the bands above 60 GHz is believed to be a higher priority, as these frequencies are not commonly used.

Demonstration and Operational Trials of Working Systems

Both the 64GHz radio link and the FSO link have operated well with no reported link failures over the installed distance of 450m.

An operational range of up to 1km for wide bandwidth connectivity using 60GHz radio is practical. Installation is simple and rapid, and suitable equipment is commercially available. Such links would appear to have multiple applications in campus networking and ‘last mile’ environments.
1 INTRODUCTION

This Report investigates the current state and future bands above 60 GHz in terms of devices, systems, applications, sharing and regulations. This study has examined the constraints imposed by propagation conditions and the operational behaviour of commercial millimetre-wave and FSO links. In addition several years’ of existing data from at least four such dual links have been analysed to provide base-line operational data.

In section 2 a wide range of applications for millimetre wave communications systems have been examined and their performance evaluated in adverse weather conditions (rain, fog and turbulence), where applicable.

The principal difficulty restricting the use of bands above 60 GHz for point-to-point telecommunications links is the device constraints on radiated power: high power devices are expensive, delicate or unavailable. A study which identifies the key obstacles to the use of frequency bands above 60GHz is presented in section 3.

The way the higher frequency bands would be utilised in various licensing scenarios is determined in section 4. In this section is also presented a survey of the regulation, systems, and applications of frequency bands specified by the ITU-R for telecommunications use, internationally. The surveying also includes commercial and academic activity in these bands.

Channels sounders are used to evaluate the typical delay spread in a range of environments where high frequency wireless connections may be used e.g. mobile telecoms and WLAN applications. A description of a channel sounder developed by Durham University is given in section 5.

A theoretical study to quantify the benefits of ATCP (Adaptive Transmit Power Control) and DFD (Dynamic Frequency Diversity) on typical short link configurations in frequency bands above 60 GHz is presented in section 6. These studies quantify interfere power in a range of meteorological conditions and calculate typical reuse distances for a range of availabilities.

Frequency bands above 60 GHz suffer severely from rain attenuation. This will put constraints upon the length or availability of links. Free Space Optical (FSO) systems
are similarly affected by the presence of fog and mist and suffer even lower availabilities. However, it is speculated that heavy rain and fog/mist rarely occur simultaneously. Therefore, frequency diverse systems, combining mm-wave and Free Space Optical (FSO) systems, have the potential to provide very high availability with reduced interference. In section 7 we present the analysis of the data collected on the 500 m range at Chilbolton, during the period April 1991 to September 1995.

Operating trials and a working demonstration of the use of a 60GHz system in an industrial environment in conjunction with a FSO link are described in section 8.
2 EXAMINATION OF SYSTEM APPLICATIONS IN THE BANDS 60 – 100 GHz

2.1 INTRODUCTION

A number of typical applications for millimetre wave communications systems have been examined and their performance evaluated in adverse weather conditions (rain, fog and turbulence), where applicable. These applications included:

- Line of sight point to point links (LOS)
- Free space optical systems (FSO) (for comparison)
- Giga bit/s Wireless LAN
- Broadband fixed wireless access (BFWA)
- Satellite communications (Satcom)
- Aero satellite communications (Aerosat)
- High altitude platform systems (HAPS)
- Mobile systems
- Short range repeaters for network backhaul
- Personal communications
- Home communications

2.1.1 Choice of RF parameters

A number of assumptions were made concerning the values of the RF parameters for these systems. The important characteristics, which are used in link budget calculations, are antenna sizes, RF power levels of the transmitters, insertion losses of wave guide connections and noise figures of the receivers. As the appropriate power levels, noise figures and insertion losses are reasonably well known at 40 GHz through earlier studies (e.g. The European Consortium studies (FP4 CRABS [1] & FP5 EMBRACE [2] projects), these were used as an initial reference point at ~ 40 GHz. Equivalent values at 100 GHz, used in an earlier Radiocommunications Agency study [3] “ A study into the theoretical appraisal of the highest usable frequencies” (AY4329), were chosen for the upper frequency (100 GHz) point. A linear interpolation between these upper and lower limits was used to derive the values for available RF power levels (figure 2.1a) and for noise figures and insertion losses (Figure 2.1b) for the subsequent performance evaluations. A background noise temperature of 280°K has been assumed to calculate the overall system noise level.

Although peak power levels above 100mw might be technologically possible, the use of such high powers in the millimetre band might not be the most cost effective solution. Lower RF powers combined with larger antennas would be a better compromise. In most of the applications discussed below, an RF power level some 10 dB below the peak level has been used to evaluate the subsequent link budgets. The RF power versus frequency relationship for these lower RF powers is shown in the yellow line in figure...
2.1a. Applications which require higher power levels are discussed in the appropriate section.

Antenna sizes, which vary depending on the application, range from very small (~1 cm for indoor applications to 2 m for satellite systems). In general, the antenna sizes used have been limited to the smallest practical sizes required to achieve an adequate margin.

2.1.2 Meteorological parameters

Gaseous specific attenuation levels (appropriate to the band 40 to 100 GHz) were obtained from ITU-R P676-5 [4] in 0.5 GHz intervals. Values of specific attenuation at the peaks of any absorption line were also included as additional information. The preliminary rain attenuation values at 0.01% and 0.1%, which were derived from ITU-R P530 [5] (and ITU-R P618 [6] for slant path systems), were estimated from values for conditions relevant to London. Fog and scintillation values were also taken from attenuation values quoted in this same report [5]. The fog densities chosen were equivalent to an optical visibility of ~200 m, which persists in the UK from between 1% and 2% of the time, depending on the location. It should be noted that the fog data used in this MET Office study [7] relates to conditions in the 1970s, where pollution levels could well have been higher than those experienced in the 21st century. The scintillation levels are derived from turbulence levels which exist for ~0.01% of the time.

Figure 2.1a: Values of maximum and realistic RF power
2.1.3 Communications system parameters

The various parameters (link length, data rate, C/N, etc) used for the subsequent system performance evaluation are shown in an associated table together with an accompanying plot of system margin as a function of frequency. It is assumed that these hypothetical communications systems operate in QPSK modulation mode and require a $C/N = 11$ dB to achieve a bit error ratio (BER) of $\sim 1$ in $10^4$. (This uncoded BER should be sufficient to achieve an error free channel performance, when operated in conjunction with both forward error correction and block error coding.)

2.1.4 Typical performance of a line of sight system on a 4km path

As an example Figure 2.2a shows the clear air margin (dark blue) achieved for of a line of sight system on a 4km path operating with a data rate in excess of 100 Mbps. The clear air margin (blue) is shown together with the reduced margins in rain, scintillation conditions and fog for the specified availabilities. The parameters, which were used to evaluate the performance, are listed in table 1. It is clear that this system could achieve...
reliability better than 99.99% of the time over most of the frequency range, except in the regions of the 60 GHz oxygen absorption line (54 to 68 GHz). Rain is the dominant effect in determining the system performance with both fog and turbulence having relatively minor effects.

Figure 2.2a: Performance of LOS applications

2.2 EVALUATION OF SYSTEM PERFORMANCE FOR SEVERAL POTENTIAL APPLICATIONS

2.2.1 Line of sight (LOS) systems

Performance has been estimated for typical point-to-point application over link lengths from 2 to 16 km. The margins achieved in rain for 99.99% and 99.9% availabilities are shown for the various path lengths in figure 2.2b and 2.2c, respectively. The effect on performance of the oxygen absorption band around 60 GHz is clearly demonstrated, where link lengths of > 2 km become impractical in the 55 to 65 GHz region. Rain attenuation becomes important for links longer than 4 km outside the 60 GHz absorption band. Although an 8 km LOS systems just achieves 99.99% availability at 40 GHz, the combined rain and gaseous attenuation above this frequency prevent this level of availability. Data rates of 150 Mbps would be achieved with QPSK modulation within the 100 MHz system bandwidth.
Table 2.1: parameters for LOS systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link length</td>
<td>2 to 16 km</td>
</tr>
<tr>
<td>Transmitter antenna diameter</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>16/10 dBm</td>
</tr>
<tr>
<td>Receiver antenna diameter</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>C/N Margin for error free channel QPSK (BER of 1 in 10^4) with additional coding</td>
<td>11 dB</td>
</tr>
<tr>
<td>Rain rate for 0.01%</td>
<td>22 mm/h</td>
</tr>
<tr>
<td>Fog visibility</td>
<td>200 m</td>
</tr>
</tbody>
</table>

Figure 2.2b: Performance of LOS applications for several path lengths at 99.99% availability
Figure 2.2c: Performance of LOS applications for several path lengths at 99.9% availability
### 2.2.2 Free space Optical systems

The performance values for the FSO system were extracted from the Terabeam data sheet (Avara™ 4221e Specifications), as this was the system purchased for the trial conducted in this project. The clear air margin has been plotted in figure 2.3, as a function of path length, together with the reduced margins achieved in rain (99.99% availability), fog (200m visibility) and scintillations (99.99% availability). The meteorological values are those appropriate to London and would differ slightly from those prevailing at the trial site at Runcorn. In particular the rainfall rate appropriate to 0.01% is ~25 mm/h and the 200 m visibility occurrence is ~ 1% for Runcorn. Although ranges up to ~3 km could be achieved in clear air (yellow), the graph demonstrates the dominance of fog in determining the system availability, where the margin (magenta) in falls to zero on a 300m path, a 200 m visibility fog. Rain and turbulence appear to have relatively similar effects, at 99.99% availabilities, in terms of system degradation. Data rates of 125 Mbps are achieved in clear air with the link margins shown.

![FSO margins as a function of path length](image)

**Figure 2.3**: FSO system performance in rain, fog and turbulent conditions

### 2.2.3 Giga bit/s Wireless LAN

The frequency bands above 60 GHz could facilitate Gigabit/s wireless LAN applications for either indoor communications in very large buildings such as an exhibition hall or enclosed spaces such as sports stadiums or large car parks. As diffraction above 60 GHz is minimal, the wireless link would need to operate as a line of sight system, although reflections and scattering from buildings could also provide another method of connection. Table 2.2 indicates the parameters used in the performance calculations. Rather than use an access point with an omni directional antenna, it seems more practical to utilise the high-gain small-size features of antennas.
characteristics in this band. A 15 dB gain antenna, which would be capable of illuminating a 90° sector from the access point, has been used for the link budget calculations. A small CPE antenna (5 cm diameter) of \( \sim 32 \) dB gain at 100 GHz (5° beam width) would need to be directed towards the access point in order to establish a connection. Data rates of \( \sim 1 \) Gbps seem possible up to several hundred metres range with oxygen absorption around 60 GHz having little impact at these short ranges. Rain fading, which for 0.01% of the time would add up to \( \sim 3 \) dB attenuation on a 300 m path, could just be accommodated over the entire frequency range. Reuse distances are examined in the next section. A margin of between 4 and 14 dB (figure 2.4a) is achieved over the frequency range in clear air.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link length</td>
<td>0.3 km</td>
</tr>
<tr>
<td>Transmitter antenna gain</td>
<td>15.0 dB</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>16/10 dBm</td>
</tr>
<tr>
<td>Receiver antenna diameter</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>700.0 MHz</td>
</tr>
<tr>
<td>Margin for error free QPSK (BER of 1 in (10^4)) with additional coding</td>
<td>11.0 dB</td>
</tr>
<tr>
<td>Rain rate for 0.01%</td>
<td>0.0 mm/h</td>
</tr>
</tbody>
</table>

Table 2.2: Parameters for Gigabit Ethernet

![Margin for Gbit wireless LAN](image)

Figure 2.4a: Giga bit/s WLAN performance
2.2.4 Broadband fixed wireless access

Broadband fixed wireless access (BFWA) might be considered as a logical extension of the high capacity Wireless LAN application discussed above. The base station/access point parameters remain fairly similar but the CPEs would require much larger antennas to cope with the increased range up to 1.5 km.

The margin calculations (figure 2.4b, below) indicates that a more than adequate system performance is achieved at 150 Mbps for better than 99.99% availability over most of the band (except above 90 GHz, where maximum range would be limited to 1.3 km), using the parameters in Table 2.3. A lower margin (~99.9%) could be maintained in the absorption band for all but 6 GHz of the band, where the margin falls below zero.

This level of performance, at data rates of ~150 Mbps or more (if 16QAM or 64QAM is deployed), would clearly be sufficient for commercial operations delivering very high capacity broadband services. Multiple sector antennas at the base station with narrower beams could raise the capacity of the base station significantly. For instance a sector angle of 15° would be achieved with a base station antenna aperture of <2 cm at 100 GHz. Thus the increased gain (plus 8 dB) could be used to raise data rates to ~700 Mbps/sector with QPSK. A base station with a capacity of ~17 Gbps would be possible, with the deployment of 24 sectors.

Although the advantages of very small reuse distances in the 60 GHz band are still available, the potential for exploiting them are diminished as the range increases. An adequate margin might be achievable at 1 km range, even in the absorption band. However, at a range over 1.5 km the extra rain attenuation and oxygen absorption could add another ~10 dB, making adequate system performance with a commercial quality of service (QoS) in the 55 to 65 GHz band very difficult to achieve over significantly more than 1 km.

In conclusion it would appear that the above 60GHz bands have considerable potential for short range (up to ~1.5 km) wireless distribution systems with several Gbps capacity for both indoor and outdoor applications.

<table>
<thead>
<tr>
<th>BFWA</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>link length</strong></td>
<td>1.5 km</td>
<td></td>
</tr>
<tr>
<td><strong>transmitter antenna gain</strong></td>
<td>20 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Transmitter power level 60/100 GHz</strong></td>
<td>16/10 dBm</td>
<td></td>
</tr>
<tr>
<td><strong>receiver antenna diameter</strong></td>
<td>0.15 m</td>
<td></td>
</tr>
<tr>
<td><strong>receiver bandwidth</strong></td>
<td>100 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Margin for error free QPSK (BER of 1 in 10^4) with additional coding</strong></td>
<td>11 dB</td>
<td></td>
</tr>
<tr>
<td><strong>rain rate for 0.01%</strong></td>
<td>22 mm/h</td>
<td></td>
</tr>
<tr>
<td><strong>fog visibility</strong></td>
<td>200 m</td>
<td></td>
</tr>
<tr>
<td><strong>Scintillation level equivalent to</strong></td>
<td>0.01 % time</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Broadband fixed wireless access parameters
2.2.4.1 Frequency re-use distances

One of the main advantages of operations in the 60 GHz absorption band is the high immunity from interference from other systems using the same band, even when located in close proximity. The peak gaseous attenuation of ~ 16 dB/km provides a wireless “fog” which allows much shorter reuse distances than in other parts of the spectrum. Figure 2.5 demonstrates this feature through calculation of carrier (C) to interference (I) ratios for several reuse distances. The wanted signal is based on a cell size of 0.5 km and the interfering signal calculated from another access point separated by distances ranging between 0.5 km to 16 km from the wanted access point. The horizontal lines indicate the required C/I for QPSK (15 dB), 16QAM (22dB) and 64QAM (30dB), respectively. It is interesting to note that even with separations as low as 0.5 km, operation is possible in a band of about 7 GHz around 60 GHz, if QPSK modulation is used. Alternatively, the separation of nodes needs to be increased to 2 km, for 64QAM. However the margins shown in figure 2.4a & b were derived for QPSK; if 16QAM is used they would be reduced by ~ 7 dB but satisfactory operation could still be achieved with 64QAM up to ~ 80 GHz on paths < 300m.
2.2.5 Satellite communications and high altitude platform systems

2.2.5.1 Fixed satellite

Table 2.4a below lists the parameters used in the evaluation of the satellite communication system margins. A 2 m diameter satellite dish could be accommodated in the Ariane 5 payload compartment. Power levels of 13 dBW have been achieved at 20 GHz for space qualified power amplifiers (TWT) more than 20 years ago for the ESA Olympus project. The projected 7 dBW at 100 GHz might be a more ambitious target for satellite amplifiers, especially if solid-state amplifiers are specified. Although achievable, the 1 metre diameter earth station antenna at 100 GHz would be a fairly costly item. The parameters used, although technically achievable, do however represent a limit of system performance for practical satellite communications systems.

The system performance evaluation (figure 2.6a) demonstrates that satellite systems above 60 GHz are not very practical even with availabilities near 99.9% of the time. This QoS is not met above 51.5 GHz. Thus even direct broadcast applications, which only require 99.7%, would not be very practical, as very large high-specification customer receiving dishes would be needed. Throughput raw data rates equivalent to one typical satellite broadcast transponder (DVB-S standard) of 33 to 36 Mbps could be achieved in 40 MHz bandwidth.
Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link length</td>
<td>36000 km</td>
</tr>
<tr>
<td>Transmitter antenna diameter</td>
<td>2 m</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>13/7 dBW</td>
</tr>
<tr>
<td>Receiver antenna diameter</td>
<td>1 m</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Margin for error free QPSK (BER of 1 in $10^4$) with additional coding</td>
<td>8 dB</td>
</tr>
<tr>
<td>Rain rate for 0.01%</td>
<td>22 mm/h</td>
</tr>
<tr>
<td>Satellite transmitter power</td>
<td>13 to 7 over frequency range dBW</td>
</tr>
<tr>
<td>Scintillation level equivalent to 0.01%</td>
<td>0.01 % time</td>
</tr>
<tr>
<td>Elevation angle</td>
<td>30 degrees</td>
</tr>
</tbody>
</table>

Table 2.4a: parameters used for satellite communication system evaluation

![Satcom performance on a 30 degree path (London)](image)

Figure 2.6a: satellite communications system performance
### 2.2.5.2 Aircraft to satellite communications

Table 2.4b lists the parameters used in the aircraft to satellite performance evaluation. As with the fixed satellite scenario system a 2 m diameter dish on the satellite is used, with transmitter power levels of 13 dBW at 40 GHz tapering down to 7 dBW at 100 GHz. However the aircraft mounted antenna would now be only 0.5 m diameter (i.e. the size of a typical satellite broadcast receiving dish).

The performance evaluation (figure 2.6b), for aircraft at heights of 5 and 10 km, demonstrates that this aeronautical satellite systems could achieve a reasonable margin (10 to 15 dB) over the entire band, except between 54 and 64 GHz, where oxygen absorption, even at these altitudes, still dominates. Passenger aircraft generally fly well above the weather, rain seldom occurring above 4 km height, except in tropical storms, which are generally avoided by high-flying aircraft. The rain attenuation effects can thus be discounted for this application. A throughput raw data rate, equivalent to one typical satellite broadcast transponder (DVB-S standard) of 33 to 36 Mbps (or equivalent to a high capacity on-board WiFi hot spot), could be achieved in the 40 MHz bandwidth.

Although the system evaluation seems to produce a reasonable margin, deployment of such a system would introduce other problems. The spot beam produced from a 2m satellite dish, in a geostationary orbit at 100 GHz, would have a diameter of ~ 100 km. An aircraft flying at ~ 800 km/h would traverse the beam in ~ 7 minutes. Even the short-haul high-density passenger aircraft services in Europe would require a complex multi-beam satellite antenna of at least 200 spot beams to provide full coverage. However a satellite system for long distance airlines, which uses these millimetre wave bands, would need a few hundred spot beams to cover typical long distance flight paths. The business case for such a complex satellite might be difficult to make, even for the high density Pacific and Atlantic routes. However the attraction of a relatively small aircraft mounted antenna is a very positive advantage.

<table>
<thead>
<tr>
<th>Aircraft to Satellite</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>link length</td>
<td>36000.0 km</td>
</tr>
<tr>
<td>transmitter antenna diameter</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>13/7 dBW</td>
</tr>
<tr>
<td>receiver antenna diameter</td>
<td>0.5 m</td>
</tr>
<tr>
<td>receiver bandwidth</td>
<td>40.0 MHz</td>
</tr>
<tr>
<td>Margin for error free QPSK (BER of 1 in 10^4) with additional coding</td>
<td>8.0 dB</td>
</tr>
<tr>
<td>satellite transmitter power</td>
<td>13.0 dBW at 40 GHz</td>
</tr>
<tr>
<td>satellite transmitter power</td>
<td>5.0 dBW at 100 GHz</td>
</tr>
<tr>
<td>Scintillation level equivalent to</td>
<td>0.01 % time</td>
</tr>
<tr>
<td>elevation angle</td>
<td>30.0 degrees</td>
</tr>
</tbody>
</table>

**Table 2.4b**: Aircraft to satellite communications
2.2.5.3 High altitude platform systems (HAPS)

The parameters used in the system performance evaluation for high altitude platform systems (HAPS) are shown in table 2.4c. RF power levels and antenna sizes are less challenging than in the SATCOM applications. However unlike the applications discussed in sections 2.2.1 to 2.2.4, the higher RF power levels (cyan curve in figure 2.1a) are required to produce viable link margins. It has been assumed that a link length of ~ 100 km is a maximum realistic range for a HAPS deployed at 20 km height, where the minimum elevation angle at the optical horizon is ~ 11°. Ground terminals with 0.2 m diameters have been chosen but increasing the size to 0.5 m diameter seems perfectly practical, if an increase in the margin of ~ 8 dB was required.

The calculated margins are shown in figure 2.6c, where a ~ 99.9% availability is just about achieved over the band from 70 to 80 GHz. This availability (~ 99.9%) would probably be sufficient for a residential service for distribution of video and broadband data in remote areas, where no alternative broadband technology (other than satellite) was applicable. It does not seem that increasing the ground terminal size to 0.5 m would significantly alter the quality of service, in terms of outage time, in most of the wave band.

It might be concluded that if HAPS is viable in the existing 47 GHz allocated band, then, provided that the RF technology is available, even higher frequency HAPS up to
80 GHz are potential viable, although outage times would be larger than those at the lower 47 GHz band.

<table>
<thead>
<tr>
<th>HAPS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>link length</td>
<td>100.0 km</td>
</tr>
<tr>
<td>transmitter antenna diameter</td>
<td>1.5 M on HAPS</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>26/20 dBm</td>
</tr>
<tr>
<td>receiver antenna diameter</td>
<td>0.2 m at CPE</td>
</tr>
<tr>
<td>receiver bandwidth</td>
<td>50.0 MHz</td>
</tr>
<tr>
<td>Margin for error free QPSK (BER of 1 in $10^4$) with additional coding</td>
<td>11.0 dB</td>
</tr>
<tr>
<td>rain rate for 0.01%</td>
<td>0.5 mm/h</td>
</tr>
<tr>
<td>HAPS transmitter power</td>
<td>0.5 dBW at 40 GHz</td>
</tr>
<tr>
<td>Scintillation level equivalent to</td>
<td>0.01 % time</td>
</tr>
<tr>
<td>elevation angle</td>
<td>11.0 degrees</td>
</tr>
</tbody>
</table>

Table 2.4c: High altitude platform systems (HAPS)

**Figure 2.6c:** HAPS system performance
2.2.6 Mobile systems communications and short range repeaters for back haul

2.2.6.1 Mobile systems communications

Mobile application using the millimetre wavebands have been studied recently (5\textsuperscript{th} framework project (EU) MBS (mobile broadband systems) [8]). The general concept of positioning base stations/access points, in American traffic lights fashion at cross roads or on lamp posts seem interesting concepts to explore. The parameters used for this application are shown in table 2.5, where a 20 dB gain base station antenna communicates with a patch antenna of a few centimetres diameter on the front and/or rear of the vehicle. More than adequate performance (~ 99.99% availability in rain) could be achieved at ranges of up to 700m for data rates of 100 to 200 Mbps (figure 2.7a) over all the band. This distance (0.7 km) probably represents the limit of range due to blockage by fixed obstacles and other vehicles.

Although such a system might be practical in the regular grid layout of the street plan of North American cities, it would be much more difficult to deploy in the more random street layouts of European cities, residential areas and rural locations. Communications systems for railways might also be another potential application.

As such systems would also have difficulty connecting directly to hand held devices, it commercial appeal might be somewhat limited. However, millimetre wave bands (~ 78 GHz) are already being seriously considered for anti-collision radar devices. Some spin off from this millimetre wave radar technology might find itself applicable to communications and control aspects associated with automatic traffic control and information systems in the future.

<table>
<thead>
<tr>
<th>mobile</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>link length</td>
<td>0.7 km</td>
</tr>
<tr>
<td>transmitter antenna gain</td>
<td>20.0 dB</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>16/10 dBm</td>
</tr>
<tr>
<td>receiver antenna diameter</td>
<td>0.05 m</td>
</tr>
<tr>
<td>receiver bandwidth (MHz)</td>
<td>100.0 MHz</td>
</tr>
<tr>
<td>Margin for error free QPSK (BER of 1 in 10\textsuperscript{4}) with additional coding</td>
<td>11.0 dB</td>
</tr>
<tr>
<td>rain rate for 0.01%</td>
<td>22 mm/h</td>
</tr>
<tr>
<td>fog visibility</td>
<td>200.0 m</td>
</tr>
<tr>
<td>Scintillation level equivalent to</td>
<td>0.0 % time</td>
</tr>
</tbody>
</table>

Table 2.5: Mobile systems communications
2.2.6.2 Short range repeaters

Lamp post mounted repeaters in these wave bands have considerable merits for hybrid systems using dual frequency bands. Millimetre wave repeaters, placed at intervals of 0.5 to 1 km in city and suburban areas, would act as both the backbone and distribution points for a lower frequency system. Lower frequency wireless LANs or mobile systems would provide the final connection to the customer terminals. Mesh systems using the very high capacity and frequency reuse capabilities of these millimetre wave bands, particularly between 55 and 65 GHz, have the potential for achieving a 5 Gbps plus back haul capacity to provision the lower-frequency short-distance broadband connections. Figure 2.7b indicates the substantial margin achieved on such a repeater link with 10 cm diameter repeater antennas over an 800 m range with a 5 GHz bandwidth (capacity ~ 7.5 Gbps).

This application could be considered as a wireless alternative to cable modem distributions through hybrid fibre coaxial (HFC) networks. The proposed hybrid wireless system has a major advantage over HFC installations in that it does not encounter the major cost of digging trenches at £50/m. If lamp post mounted repeaters are used AC power is already available for the repeaters. Backhaul bandwidth in excess of ~ 5 GHz combined with customer connections well in excess of 100 Mbps (e.g. equivalent to the maximum rates of IEEE 802.11n) could be achieved.
Figure 2.7b: Performance of repeater link with data rate of ~ 7.5 Gbps

2.2.7 Personal communications and home networks

2.2.7.1 Personal communications

One of the very short-range applications considered was that of personal communication between “worn” electronic monitoring devices and a pocket computer. Ranges are necessarily short < 2m but the path profile would be anything but line of sight. Millimetre wave are nor particularly suitable for such applications for two reasons:

- Their ability to penetrate or bend around obstructions is poor
- The low antenna directivities required for personal communications are generally produced by very small apertures. This can result in very high power densities, which approach safety levels.

Table 2.6a indicates the parameters chosen for the evaluation, where antenna gains of 0 dB were used. Even at a data rate of 10 Mbps, it is difficult to sustain with a high margin (figure 2.8a) even when free space path loss is assumed. Power levels of the
transmitter needs to be reduced to ~ 10 mw or less to comply with safety regulations. This short-range application does not take advantage of the high gains, which can be achieved with relatively small antennas in this band. Path losses would be expected to be much greater than free space. However due to the very short range (2m) rain attenuation is not an issue but wetting of antennas in damp conditions might be more problematic.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body communications</strong></td>
<td></td>
</tr>
<tr>
<td>link length</td>
<td>2</td>
</tr>
<tr>
<td>Transmitter power level 60/100 GHz</td>
<td>0/0 dBm</td>
</tr>
<tr>
<td>Nominal transmitter antenna diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Nominal receiver antenna diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>near field</td>
<td>2D^2/\text{wavelength} m</td>
</tr>
<tr>
<td>receiver bandwidth</td>
<td>10.00 MHz</td>
</tr>
<tr>
<td>C/N Margin for error free channel QPSK (BER of 1 in 10^4) with additional coding</td>
<td>11.00 dB</td>
</tr>
<tr>
<td>antenna size</td>
<td>1 cm^2</td>
</tr>
<tr>
<td>power density at 40 GHz at maximum device power</td>
<td>0.01 W/cm^2</td>
</tr>
</tbody>
</table>

**Table 2.6a**: Body communication system parameters

**Figure 2.8a**: personal communications performance
2.2.7.2 In house (Home) communications

In house or home communications are another potential application of millimetre wave systems. However, the same problems that occurred with personal communications are encountered when these wave bands are applied to home communications. Short ranges with non-line-of-sight paths, combined with low-gain antennas and power flux density restrictions, reduce the practical link margins. The minimal effect of oxygen absorption can be detected in the slight kink in the curve around 60 GHz.

The performance evaluations (Table 2.6b and Figure 2.8b) on paths up to 20 m length, assuming again only free space loss, produce margins of only 15 to 20 dB. This is hardly adequate for paths, which could be anything but line of sight with the added attenuation of transmission through building walls. Communications at millimetre wave might be possible within one room, as scattering from walls could produce an adequate signal level. Thus provided RF devices could be produced at a very low cost, these bands might become applicable for much higher data rate “Bluetooth” type applications.

<table>
<thead>
<tr>
<th>Home wireless network</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>link length</td>
<td>20 m</td>
</tr>
<tr>
<td>Transmitter power level</td>
<td>10 dBm</td>
</tr>
<tr>
<td>transmitter antenna gain</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>receiver antenna diameter (D) (gains of 10 to 20 dB)</td>
<td>1 cm</td>
</tr>
<tr>
<td>receiver bandwidth (MHz)</td>
<td>25.0 MHz</td>
</tr>
<tr>
<td>Margin for error free FSK (BER of 1 in 10^4) with additional coding</td>
<td>11.0 dB</td>
</tr>
</tbody>
</table>

Table 2.6b: In house(Home) communications

![Margin (dB) for home wireless network with range of 20 m](image)

Figure 2.8b: In house (Home) communications
2.3 CONCLUSIONS

2. Millimetre wave communications systems at frequencies above 60 GHz have the potential for very high capacities, especially as more than 10 GHz of bandwidth is available in the current frequency allocations.

3. Spectrum that is not subject to the oxygen absorption effect exhibits behaviour which is broadly similar to spectrum below 60GHz where, in the absence of precipitation fading, the limit of propagation is the horizon.

At frequencies around 60GHz, the oxygen absorption band, with its peak attenuation of ~ 16dB/km, produces the radio equivalent of a fog, thus suppressing long distance transmissions. As a consequence the distance at which a frequency channel can be “re-used” is much shorter. The re-use distance can reduce to as little as ~ 1 km in certain scenarios. This provides an increase in spectral efficiency as frequencies may be re-used with minimal co-ordination distances.

4. Specific applications have been identified that require broad contiguous blocks of spectrum e.g. radio transmission of gigabit ethernet services.

5. Millimetre wave communications applications need to operate over short paths (< 10km) and also need to take advantage of the high antenna gains and directivities, which can be achieved with small antenna sizes (typically 10 < diameter < 30cms).

6. Two applications have been identified for further study. These are:
   a. Wireless local area networks providing ~1Gbps capacity through millimetre wave access points.
   b. Very high capacity backhaul for either MESH or branch and tree networks, operated in conjunction with very local wireless distribution services at lower frequencies.

7. The exploitation of these bands requires the development of low-cost RF technology.

8. Millimetre wave systems are not particularly suited to situations where long range is required e.g. satellite or HAPS systems or where non-line of sight paths are experienced (e.g. personal communications and home networks).

9. Millimetre wave systems, at ranges of more than 100m, provide a much better quality of service, in adverse weather conditions (rain and fog), than free space optical (infra red) systems.

Table 2.7 contains a summary of the results obtained from the study of applications for systems in the frequency band 60 to 100 GHz. Typical system parameters have been assumed such as 35 cm diameter antennas for the line of sight application and 15 dB
Radio Systems at 60GHz and Above

gain (90° sector horns) for the hub in BFWA systems. Rain attenuation values for 0.01% outage for London, UK have been used to evaluate system performance.

The RF parameters were assumed to be those which might be achieved in a 5 year time scale. Maximum RF power levels were assumed to reduce with frequency, from ~ 26 dBm at 60 GHz tapering off to 20 dBm at 100 GHz. However for most applications these power levels were reduced by 10 dB, as a combination of larger antennas with lower power transmitters seems a more practical solution. Noise figure increased with frequency from 2.4dB at 60 GHz to 4 dB at 100GHz.

<table>
<thead>
<tr>
<th>System Application</th>
<th>Frequency range (GHz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line of sight point to point links (LOS)</td>
<td>55 to 65</td>
<td>Link lengths &gt; 2 km impractical due to gaseous and rain attenuation</td>
</tr>
<tr>
<td></td>
<td>65 to 100</td>
<td>Link lengths up to 4 km possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Both with data rate of 150 Mbps for 99.99% availability</em></td>
</tr>
<tr>
<td>Free space optical systems (FSO) (for comparison)</td>
<td>IR bands 1.5 to 0.9 μm</td>
<td>Typical system achieves only 99% availability on paths of ~ 200m due to fog</td>
</tr>
<tr>
<td>Giga bit/s Wireless LAN</td>
<td>60 to 100</td>
<td>Short range (~ 300 m) system operating at 1 Gbps with small antennas (~ 5 cm aperture) will achieve working margin even in rain (99.99% availability) assuming line of sight connections</td>
</tr>
<tr>
<td></td>
<td>55 to 65</td>
<td>Very short frequency reuse distances (~1 km) possible (see BFWA)</td>
</tr>
<tr>
<td>Broadband fixed wireless access (BFWA)</td>
<td>55 to 65</td>
<td>Operational margin up to 1 km; reuse distances ~ 1km</td>
</tr>
<tr>
<td></td>
<td>60 to 80</td>
<td>Operational margin up to 1.5 km; reuse distances ~ 2km</td>
</tr>
<tr>
<td></td>
<td>80 to 100</td>
<td>Systems use QPSK, 150 Mbps and 99.99% availability; very high capacity possible</td>
</tr>
<tr>
<td>Satellite communications (Satcom)</td>
<td>53 to 67</td>
<td>Satcom not practical due to very high oxygen absorption</td>
</tr>
<tr>
<td></td>
<td>67 to 100</td>
<td>&lt; 99.9% availability for capacity ~ 40 Mbps technology stretch to limit to achieve even this poor level of performance</td>
</tr>
<tr>
<td>Aero satellite communications</td>
<td>54 to 65</td>
<td>Aero satellite not practical in this band due to very high oxygen absorption</td>
</tr>
<tr>
<td></td>
<td>65 to 100</td>
<td>Operational margin for 40 Mbps service achieved as rain attenuation above 5 km is zero. However very small spot beams of 100 km diameter.</td>
</tr>
<tr>
<td>High altitude platform systems (HAPS)</td>
<td>52 to 70</td>
<td>Not practical for HAPS</td>
</tr>
<tr>
<td></td>
<td>70 to 100</td>
<td>Availability near 99.9% for service at ranges up to 100 km</td>
</tr>
<tr>
<td>Mobile systems</td>
<td>55 to 100</td>
<td>99.99% availability over almost all frequency range up to 1 km for 100 Mbps service. Small patch antennas (5 cm diameter) on vehicle with American traffic light</td>
</tr>
</tbody>
</table>

35
Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Application</th>
<th>Frequency Range</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short range repeaters for</td>
<td>55 to 100</td>
<td>99.99% availability over 0.5 to 1 km paths with very high capacity (5 Gbps); very short reuse distances, similar to BFWA in 55 to 65 GHz band</td>
</tr>
<tr>
<td>network backhaul</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal communications</td>
<td>55 to 100</td>
<td>RF power limited by safety; low gain antennas and non line of sight scenario. Application not really suitable for these frequency bands</td>
</tr>
<tr>
<td>Home communications</td>
<td>55 to 100</td>
<td>Similar restrictions apply to personal communications. RF power limited by safety; low gain antennas, non line of sight conditions and very poor wall penetration. Application not really suitable for these frequency bands</td>
</tr>
</tbody>
</table>

Table 2.7: Summary of characteristics of various applications

2.4 REFERENCES

3. “A study into the theoretical appraisal of the highest usable frequencies” Radio Communications Agency Project (ref AY 4329)
5. “Propagation data and prediction methods required for the design of terrestrial line of sight systems”, Recommendations ITU-R P530-10, ITU Geneva
3 IDENTIFICATION OF KEY OBSTACLES TO BAND USE

3.1 INTRODUCTION

Unlike lower frequencies, semiconductor integrated circuits do not provide the complete answer at millimetre waves. Significant amount of the product size and cost consists of passive components based on waveguide structures, used for implementing and enclosing filters, diplexers, gain stages and interconnects. This complex of plumbing must be replaced by a technology that can scale down in cost as market size and applications expand. The radio link must evolve in cost effectiveness in a manner similar to the cellular phone, the PC and digital cameras. New architectures must be developed with a low-cost appliance-design mindset.

During the last twenty years there has been a general trend towards higher frequencies. A review of the current status of transmitter and receiver technology for higher frequencies (above 60GHz) is presented in this section under the title “Classical solutions”. This review is a giving general understanding of the potentials of the current technology.

However the trend towards the higher frequencies is in large part a consequence of technology development driven by scientific applications in astronomy and remote sensing. Concentrating in the frequency range 60 to 100GHz and the commercial applications presented in section 2 the receiver and transmitter technology is also discussed from a more practical point of view based on the most recent solutions (after 2000).

3.2 TRANSMITTER TECHNOLOGY

3.2.1 Classical solutions

For generating CW (Continuous Wave) power a variety of electron vacuum and diode structures can be used, all of which fall into one of four categories:

- Direct generation at the frequency of interest.
- Up conversion from a lower frequency
- Down conversion form a higher optical frequency.
- Power Combining

Three aspects of performance are considered:

- Available power
- Bandwidth
- Frequency and phase performance.
**Direct generation at the frequency of interest**

**Solid-state:** Solid-state sources are finding an increasing number of applications as sources of microwave power in the frequency range 1-100GHz. These sources are reasonably compact, affordable and practical for most millimetre-wave applications. In addition amplifier products are provided to enhance the power generation capability of the basic oscillators or other sources such as up-converters and frequency multipliers.

Several different devices are employed to produce these sources. The most commonly used devices are: Gunn Diodes (Gallium Arsenide-GaAs and Indium Phosphide-InP), IMPATT diodes (Silicon and Gallium Arsenide) and GaAs FET.HEMT and other three-terminal devices. The frequency of operation, power output, tenability and other performance characteristics determine which device will provide optimal results and a cost-effective solution. [1, 2, 3]. Figures 3.1 and 3.2 show the output power of Gunn and IMPATT diodes as a function of frequency. In frequency range of our interest (60-100GHz) the power decreases as the inverse of frequency.

![Figure 3.1: Output power of Gunn diodes as a function of frequency.](image-url)
Gunn and IMPATT diodes are the most commonly used active devices for tunable oscillators. Gunn diode oscillators using GaAs or InP diodes operate over the 18 to 170 GHz with power levels ranging from a few milliwatts at the high frequency end to about 400 mW at the lower frequencies. These oscillators are mechanically tunable over a fairly wide range, offering up to 40% of their centre frequency. A limited amount of electrical tuning is achieved either by varying the bias voltage or through the use of a tuning varactor within the oscillator. Gunn oscillators generally produce very low noise content and a free of spurious signals. They make excellent sources for local oscillator, transmitters and signal generators. These oscillators can be phase-locked to a low phase noise, high stability reference signal at RF of microwave frequencies.

**Vacuum electron devices:** There are many designs of vacuum electron tube, yielding power from frequencies as low as a few GHz right up into the THz part of the spectrum. The methods by which the radiation is generated vary, but all tubes contain a source of electrons - usually a heated cathode - and a subsequent accelerating potential to create an electron beam. A good review of the various operating principles of the various devices has been made by Bhartia and Bahl, [4]. This text also discusses the range of frequency obtained from each tube type (namely klystrons, backward wave oscillators and gyrotrons) as summarised in the Figure 3.3.
Radio Systems at 60GHz and Above

Figure 3.3: High frequency capability of vacuum tube devices.

The klystron was one of the first tubes utilised for the generation of millimetre waves, and the particular design used at high frequencies is known as the reflex klystron. The conventionally manufactured reflex klystron, which is limited to frequencies of about 200 GHz [4], has an output power of about 10 mW and a mechanical tuning range of only a few GHz.

In a backward wave oscillator (BWO) an electron beam interacts with radiation propagating in the opposite direction along the slow wave structure. Energy is coupled from the electron beam to the wave, leading to amplification of the latter. A magnetic field is applied parallel to the tube axis to confine the electron beam. Characteristic of BWOs developed in the past by Thompson-CSF are presented in the following table. The table also points to the limited tube lifetime, a problem which is believed to persist to date.

<table>
<thead>
<tr>
<th>Tube Type</th>
<th>Centre Frequency (GHz)</th>
<th>Power Output (W)</th>
<th>Bandwidth (GHz)</th>
<th>Voltage (kV)</th>
<th>Current (mA)</th>
<th>Average Life (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO80</td>
<td>40</td>
<td>10-40</td>
<td>1</td>
<td>3-6.9</td>
<td>60-80</td>
<td>5000</td>
</tr>
<tr>
<td>CO40</td>
<td>70 or 74</td>
<td>3-15</td>
<td>3</td>
<td>3-6</td>
<td>60</td>
<td>4000</td>
</tr>
<tr>
<td>CO20</td>
<td>136 or 154</td>
<td>1.5-3</td>
<td>2-4</td>
<td>3-6</td>
<td>60 (max)</td>
<td>2000</td>
</tr>
<tr>
<td>CO10</td>
<td>282</td>
<td>0.2-1</td>
<td>15</td>
<td>5-11</td>
<td>30 (max)</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 3.1: Typical Characteristics of BWOs. Tubes manufactured by Thompson-CSF France
Radio Systems at 60GHz and Above

The backward wave oscillator is a very useful laboratory source of CW radiation. However, it has fundamental drawbacks (expensive, short operation time, high required Voltage for operation) for commercial use for the application discussed in section 2.

Up conversion from a lower frequency

The generation of harmonic frequencies from a fundamental frequency source has been the traditional method of providing LO power within the millimetre and sub-millimetre wave region. In concept, generation of power through frequency multiplication is simple. Low frequency power is introduced into a non-linear circuit element; power generated by the non-linearity at a selected harmonic is subsequently output. Invariably, a semiconductor diode is used to generate the desired harmonic, and circuit filters reject unwanted frequencies.

The following figure shows a typical example of a frequency multiplication scheme in which a fundamental oscillator (a Gunn oscillator or voltage controlled oscillator etc.) is applied to a diode multiplier. The output of the multiplier can, by design of the embedding circuit, provide different harmonic content and hence different degrees of frequency up-conversion, i.e., multiplication.

![Figure 3.4](image)

**Figure 3.4**: Schematic of a typical (sub) mm wave frequency up-converter system

The advantages of frequency up-conversion include:

- Relative ease of implementation at frequencies of our interest (60-100GHz)
- Use of low power, solid state technology;
- Multiplier structures are relatively straightforward to interface to a heterodyne mixer via, for example, a feedhorn antenna or by direct connection using fundamental mode waveguide; and
- Solid state power generation through frequency multiplication has an excellent heritage of use in numerous ground based, airborne and space borne heterodyne radiometers.
Planar varactor/varistor diode multipliers: Frequency multiplier designs that attempt to terminate harmonic frequencies within the internal circuit through cunning balanced arrangements have generally proved impractical with whisker contacted varactor and varistor diodes. Planar diode technology has several advantages:

- Circuits are easier to assemble, and rugged;
- Planar diode technology allows the possibility of balanced diode designs that terminate harmonics within the diode circuit, thus simplifying the RF circuit. In principle this permits more efficient frequency multiplication at a higher harmonic number;
- It allow greater predictability in circuit fabrication, and consequently is more amenable to computer aided circuit design; and
- It allows the possibility of integrating small arrays of diodes, with consequent improvements in power handling.

In concept, the monolithic circuit, in which active diode is fabricated on the native circuit substrate, is straightforward [5]. Air bridges are generally used to reduce the parasitic capacitance, together with proton isolation to reduce parasitic conduction. Disadvantages of the monolithic circuit are that it is manufactured for a specific application (and therefore may be costly), and becomes very small as the frequency increases. RF circuit losses may be high. The Jet Propulsion Laboratory (JPL) and the University of Virginia (UVA) have developed processes (e.g., the UVA MASTER processes) for the integration of the active diode element with the RF circuitry on a quartz substrate (described in the following section). JPL has taken device fabrication a stage further with the MOMED diode [6]. Multiplier designs that incorporate this concept [7] have been reported with good efficiency, using integrated varactors in a balanced configuration. However, there remains the problem of poor heat sinking, and consequently, for frequency multipliers, the input power is currently limited to around 40mW.

HBV Diode multipliers: Since 1980 most frequency multipliers have used varactor, or varistor diode technology. The recent invention of the heterostructure barrier varactor diode (HBV) at Chalmers University, offers a promising alternative to the Schottky barrier varactor diode. In concept, the HBV uses material engineering to stack several varactors on top of each other. Thin barriers of high band gap material are positioned between the modulation regions in order to prevent unwanted parasitic current flow. This approach has the advantage that for higher frequencies and powers the intrinsic device area can be maintained without a subsequent increase in its capacitance.

A further attractive feature of the HBV is its symmetrical CV characteristic, which occurs because there is no Schottky contact formation. When used to frequency multiply, the HBV inherently produces only odd order harmonics. As in the case of balanced pairs of Schottky varactor diodes, this simplifies the RF circuit design, since fewer harmonic terminations need to be simultaneously optimised, and allows the possibility of frequency multiplication factors of 3, 5 or even 7. The HBV has also
shown itself to be able to handle high input powers, and sub-millimetre HBV multipliers have exhibited maximum efficiencies at input powers of 150mW compared with ~40mW for the single Schottky barrier varactor diode [8].

Figure 3.5 : Planar HBV tripler, illustrating internal waveguide circuit and diode

Down Conversion from a higher optical frequency

Photomixing: Photomixers are optical heterodyne devices, converting the difference frequency between two visible or near infrared laser beams into an oscillating electromagnetic field in the GHz or THz range. Photodiode technology has advanced significantly in the last few years due to the movement of the telecommunications industry towards ever increasing data rates. The need for low loss and high bit rates requires highly transparent, low dispersion fibres, which is provided by specialised inorganic glasses operating predominantly at wavelengths around 1.55 µm

Power Combining

It is possible to raise the output power of solid state oscillators through the use of power combining techniques. These permit the outputs of several devices to be coherently added, thus increasing the available output power.
Two different power combining principles have been utilised: a) an open cavity Fabry-Perot resonator and b) a waveguide structure.
In the first approach [9], the individual Gunn diodes are coupled by reflection from the curved mirror and power is optimised by translating the laminae in the grooved mirror. Recent refinements in this quasi-optical technique have enabled powers of 90 mW to be realised at 90 GHz from fundamental mode InP diodes. One advantage of this power combiner design is that the frequency may be stabilised by applying feedback to one diode only.

A second approach has incorporated two appropriately spaced InP Gunn devices in a rectangular waveguide cavity [10]. The power extracted at 100 GHz was 300 mW.
**Available Transmit Power**

Figure 3.8 illustrates the power outputs available from various sources over a range of frequencies. This figure deliberately includes frequencies much higher than our area of interest (60-100GHz) for a better understanding of the potentials of the different sources. We can see that the available power decreases as the frequency increases. What is mentioned here applies also to the Local Oscillators.

![Available Output Power](image)

**Figure 3.8:** Available output powers from different devices

The available power summary should be used with care. Only those devices are included which show most promise. The following Tables summarize the various devices.

**Technology Potential**

<table>
<thead>
<tr>
<th>Source</th>
<th>Current availability</th>
<th>Potential availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunn diodes</td>
<td>20dBm at 100 GHz, but availability decreasing (difficult to obtain InP diodes)</td>
<td>In principle, + 20dBm at 150 GHz in 10 years, if diode technology is developed</td>
</tr>
<tr>
<td>Power amplifiers</td>
<td>20dBm at 100 GHz, but limited source (TRW, Inc.)</td>
<td>Expect up to +20dBm at 200 GHz within 10 years</td>
</tr>
<tr>
<td>Frequency multipliers</td>
<td>For power see chart</td>
<td>Further development in hand. A goal of 1 mW at 1 THz is thought to be realistic</td>
</tr>
<tr>
<td>BWOs</td>
<td>Mature technology</td>
<td></td>
</tr>
<tr>
<td>Photonic mixers</td>
<td>~1mW at 200 GHz</td>
<td>10 mW at 200 GHz, (development of better diode technology)</td>
</tr>
</tbody>
</table>
Radio Systems at 60GHz and Above

**Bandwidth**

<table>
<thead>
<tr>
<th>Source</th>
<th>Bandwidth</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunn diodes</td>
<td>Typically a few percent of the centre frequency</td>
<td>Available power decrease with tuning range</td>
</tr>
<tr>
<td>Frequency multipliers</td>
<td>Typically a few percent of the centre frequency</td>
<td>In principle possible to tune; but difficult, as is the design of wideband multiplied sources</td>
</tr>
<tr>
<td>Power amplifiers</td>
<td>Wideband</td>
<td>Only limited by bandwidth of amplifier</td>
</tr>
<tr>
<td>BWOs</td>
<td>Depends on type of structure</td>
<td></td>
</tr>
<tr>
<td>Photonic mixers.</td>
<td>Tuneable</td>
<td>Wide band sources, easy to tune by changing laser frequency</td>
</tr>
</tbody>
</table>

**Convenience**

<table>
<thead>
<tr>
<th>Source</th>
<th>Convenience</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunn diodes</td>
<td>Excellent, typical solid state diode component</td>
<td></td>
</tr>
<tr>
<td>Frequency multipliers</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Power amplifiers</td>
<td>Excellent</td>
<td>Limited only by bandwidth of amplifier</td>
</tr>
<tr>
<td>BWOs</td>
<td>Inconvenient</td>
<td>Limited lifetime, HV power supply, Russian technology</td>
</tr>
<tr>
<td>Photonic mixers.</td>
<td>Good</td>
<td>Requires laser power supplies</td>
</tr>
</tbody>
</table>

**Frequency and Phase Characteristics**

In general, free running oscillators are not very stable, whether a Gunn diode, electron tube or optical laser. Frequency and phase stability are best achieved by locking the oscillator to a lower frequency standard. In this case phase noise is generally related to the lower frequency standard, degraded by the relevant multiplication standard.

Stability $(\Delta f/F) < 1 \times 10^{-9}$ and a frequency placement of $< 1$kHz have been routinely demonstrated at frequencies up to ~300 GHz.

### 3.2.2 Recent Transmitter technology for 60-100GHz

The transmitter provides a carrier signal modulated by the data to be transported across the radio link.

Transmitters can be configured to operate using linear devices or within the saturated region of the active devices.

In all cases a source of carrier signal is required. This may be a fundamental mode oscillator or can be derived from a carrier source operating at a sub-multiple of the output frequency followed by a multiplier. Fundamental operation conceptually requires the smallest number of active devices. However at high mm-wave frequencies it can be
less cost effective particularly if feedback stabilization is required to provide frequency stability. In addition it is necessary to provide isolation between the oscillator and any sources of variable return loss to avoid the oscillator being de-tuned by the load presented by an antenna, modulator or other circuit elements.

**Figure 3.9:** Direct frequency modulation of the source.

In an FM (frequency modulated), or CPM (continuous phase modulation) transmitter the data stream can / is restricted in bandwidth using a pulse shaping filter. This allows the bandwidth of the transmitted signal to be restricted. This filter is normally implemented at the base-band frequency range of the modulating signal. Subsequent amplifier / multiplier stages can be operated in a saturated region without causing the spectrum to degrade such that the transmission bandwidth is increased. This allows the transmitter to operate with maximum power for a defined size of active device (See Figure 3.9).

**Figure 3.10:** Direct modulation following the source.

The source can be followed be a modulation stage (Figure 3.10) using an amplitude or phase modulator. This device can be operating in a linear region or as a non-linear device, for example a phase reversing switch or an opto-electric modulator. Whilst it is conceptually possible to operate on the RF channel with a channel shaping filter this is not generally practical for systems in the mm-wave region. Thus if any non-linear elements are present in the modulator or subsequent stages the transmit spectrum will exhibit a sin(x)/x response and will occupy significantly more spectrum than the minimum necessary from a Nyquist consideration.
Figure 3.11: Linear up-conversion of a modulated carrier.

A linear up-converter can be realized using an up-converting mixer followed by a band selection filter and linear amplifier (Figure 3.11). This type of approach can support any form of modulation subject to the linearity of the mixer and amplifier maintaining an appropriate EVM (error vector magnitude).

The three technical approaches, briefly described above, form the basis of today’s commercial supply market at 57-64GHz.

A hybrid approach can be implemented using a source and modulator / up-converter operating at a sub-multiple of the output frequency. This is then followed by a multiplier stage to achieve operation at the final output frequency. This approach is only suited to constant envelope forms of modulation unless spectrum expansion due to \( \sin(x)/x \) can be accepted.

This fourth approach is used by the Durham 60GHz channel sounder.

### 3.3 RECEIVER TECHNOLOGY

#### 3.3.1 Classical Solutions

Heterodyne mixer receivers (see Figure 3.12) which use high speed Schottky diodes for the non-linear mixing element have been demonstrated at all frequencies up to at least 2,500 GHz.

Single moded waveguide, and corrugated feedhorn technology can be manufactured by traditional, or micro-machining techniques for use at all sub-millimetre frequencies. Superconducting mixer elements (superconducting tunnel junctions, hot electron bolometers) routinely provide low noise performance approaching the quantum limit.
Figure 3.12: Heterodyne mixer receivers

The mixer stage is usually acknowledged as being the noisiest stage in the receiver so an RF amplifier is positioned ahead of it to mask that noise with a higher signal level. The RF-amplifier provides amplification for the signal as soon as it arrives from the antenna. The amplified signal is then passed to the "mixer/oscillator". The purpose of the mixer/oscillator is to translate the frequency of the incoming signal to the "intermediate frequency", i.e. to the "IF amplifier". However as the frequency increases the received signal cannot be amplified always directly (due to limitations of the receiver technology at higher frequencies) but has to be down-converted first.

Amplifier Technology

At frequencies up to ~60 GHz, RF signal amplifiers are available from several commercial suppliers. At higher frequencies, however, receivers may be manufactured for a specific application and therefore may be costly. For example, InP MMIC amplifiers developed by JPL/TRW are being used on the ESA Planck Low frequency Instrument (LFI) instrument at 90 GHz, and InP HEMTs (available from Hughes) are being used in the NASA Microwave Anisotropy Probe (MAP) space instrument at similar frequency (custom built by the National Radio Astronomy Observatory).
Diode Mixer Technology

There have been significant developments in diode mixer technology in recent years.

It has been demonstrated that planar technology can give excellent performance at all millimetre and sub-millimetre wavelengths (even up to 2,500 GHz).

Corrugated waveguide feedhorns for coupling to free space and waveguide mount structures have been demonstrated to frequencies in excess of 2,500 GHz.

Fixed tuned waveguide mixer mounts have demonstrated excellent broadband performance.

Receiver Performance

Figure 3.14 summarizes the current performance of receivers. This figure deliberately (as Figure 3.8) includes frequencies much higher than our area of interest (60-100GHz) for a better understanding of the potentials of the different receivers.
**Radio Systems at 60GHz and Above**

**Figure 3.14:** Summary of available receiver performance

**LO Requirements**

The difficulty in generating power has been outlined in the section on ‘Transmitters’. In turn, this creates a problem for heterodyne receiver systems, because of the heterodyne requirement for Local Oscillator (LO) power.

<table>
<thead>
<tr>
<th>Mixer type</th>
<th>LO power requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single ended diode mixer</td>
<td>~1 mW at fundamental frequency</td>
</tr>
<tr>
<td>Sub-harmonic diode mixer</td>
<td>~3 mW at half the fundamental frequency</td>
</tr>
<tr>
<td>Superconducting mixer</td>
<td>few μW/s at fundamental frequency</td>
</tr>
</tbody>
</table>

**Receiver Potential**

<table>
<thead>
<tr>
<th>Source</th>
<th>Current availability</th>
<th>Potential availability</th>
</tr>
</thead>
</table>
| Diode mixer | Reasonable availability from commercial sources at frequencies up to 400 GHz  
Available from specialist suppliers at frequencies up to 1,000 GHz | All solid state receivers exist now at < 500 GHz; expect all solid state receivers up to 1 THz within 10 years  
Expect sensitivity to improve by less than a factor of 2 during next ten years |
| SIS mixer    | Only available from specialist suppliers                                           | Available now – but cooling inconvenience likely to remain  
No major increase expected in sensitivity                                                |
| HEB mixer    | Only available from specialist suppliers                                           | Available now – but cooling inconvenience likely to remain  
No major increase expected in sensitivity                                                |
Radio Systems at 60GHz and Above

**Bandwidth**

<table>
<thead>
<tr>
<th>Source</th>
<th>Bandwidth</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode mixer</td>
<td>Full waveguide band</td>
<td>Limited by the LO injection network, and IF matching circuit</td>
</tr>
<tr>
<td>SIS mixer</td>
<td>Full waveguide band</td>
<td>Limited by the LO injection network, and IF matching circuit</td>
</tr>
<tr>
<td>HEB mixer</td>
<td>Limited to a few GHz</td>
<td>Limited to low IF frequencies by the device operation</td>
</tr>
</tbody>
</table>

**Convenience**

<table>
<thead>
<tr>
<th>Source</th>
<th>Convenience</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode mixer</td>
<td>Excellent</td>
<td>Typical solid state diode component, similar in operation to those at microwave frequencies</td>
</tr>
<tr>
<td>SIS mixer</td>
<td>Inconvenient - requires cooling</td>
<td>requires quite complicated cooling system</td>
</tr>
<tr>
<td>HEB mixer</td>
<td>Inconvenient - requires cooling</td>
<td>requires quite complicated cooling system</td>
</tr>
</tbody>
</table>

3.3.2 Recent Receiver technology for 60-100GHz

Figure 3.15 shows a Receiver Topology. (A more detailed diagram that Fig.3.12)

**Figure 3.15.** Heterodyne receiver structure.

The receiver is generally realized as a heterodyne system.

In this approach the incoming spectrum to the receiver is down-converted using a mixer and local signal source. The local signal source can be derived in a similar means to that used at the transmitter.

Since the power levels are generally lower in the receiver than in the transmitter it is also possible to use a mixer that is “pumped” by a local signal source operating at a sub-multiple of the effective frequency.
This can result in a less efficient mixer performance. However this can be mitigated by the inclusion of a low noise amplifier between the antenna and the down-converting structure.

If a low noise amplifier is included in the signal path to the mixer then a method of attenuating the noise power in the image response frequency band for the converter. This requires either an additional filter of the use of an image rejecting mixer structure. This structure requires two identical mixers with two sets of local source power to the mixers.

When the receiver is deployed within a terrestrial link the noise power present in the receiver is due to both the self noise of the receiver and the noise due to the temperature of anything present within the beam of the antenna. At mm-wave with moderate to high antenna directivity this usually includes ground and building clutter at ~300 Kelvin. This has the effect of raising the apparent noise floor of the receiver. With a receiver noise figure of 3dB this can be degraded to 6dB. With a receiver noise figure of 6dB this can be degraded to 7.8dB.

Low noise figure requires additional gain prior to the mixer stages within the receiver. Since the mixer stages provide the large signal distortion limits of the receiver high levels of pre-mixer gain reduces the maximum signal levels that can be tolerated by the receiver.

A trade off between noise figure and is required. A system noise figure of 7 dB to 10 dB is usually practical for commercial systems.

### 3.4 COST OF TECHNOLOGY

It is extremely difficult to predict the future cost of technology. The following table is an estimate of the current cost of some of the more critical components.

There is no intrinsic reason why the technology is more expensive than more established lower frequency microwave technology. In fact, because the ‘active circuits’ and components are generally smaller, they could in principle be cheaper.

Current cost strongly reflects the small numbers and specialist nature of the technology; increased demand will drive a dramatic drop in cost.

The cost of diode mixers operating at frequencies less than ~500 GHz has substantially decreased in real terms during the last 5 years, by at least a factor of 2. This is a consequence of increased familiarity, increased demand and more suppliers.
Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Transmit components</th>
<th>&lt; 5K GBP</th>
<th>5 – 20K GBP</th>
<th>20-50K GBP</th>
<th>&gt;50k GBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunn</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Varactor multiplier</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gunn + multiplier</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BWO tube</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIR laser</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receive components</th>
<th>&lt; 5K GBP</th>
<th>5 – 20K GBP</th>
<th>20-50K GBP</th>
<th>&gt;50k GBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 GHz amplifier</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode mixer (up to 200 GHz)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Price strongly depends on number purchased

3.5 CONCLUSIONS

In general transmitter/receiver technology has been developed significantly the last years due to the trend towards higher frequencies. A variety of solutions have been proposed in terms of components and system hardware. At the highest frequencies these solutions might be relative specialized, limited in performance and expensive.

However at the frequency range 60 – 100 GHz transmitter/receiver technology is reasonably mature and mass-produced systems are commercially available (see sections 3.2.2 and 3.3.2). For example transmitters with 10mW output power and receivers with 10dB Noise Figure are available today to fulfill the radio link requirements for the applications presented in section 2.

3.6 REFERENCES

2. www.millitech.com
3. www.castlemicrowave.com
4 IMPLICATIONS OF LICENSED AND LICENCE-EXEMPT USE & A SYRVEY OF INTERNATIONAL ACTIVITY IN BANDS 60-100 GHz

4.1 INTRODUCTION

An international survey has been conducted into regulation, systems and applications of frequency bands specified by the ITU-R for telecommunications use. The objective of the survey was to determine how the higher frequency bands would be utilised in various licensing scenarios (e.g. no, light touch and fully managed licensing). In support of this, national regulators, voluntary standardisation bodies and commercial organisations have been approached.

The main bands of interest internationally are 60-61, 64-66, and 71-76/81-86 GHz.

4.2 CURRENT UK POSITION

The current UK position may be summarised on the basis of the document ‘United Kingdom Frequency Allocation Table 2004, Issue No. 13’, which is reproduced as Annex 6 of this paragraph (FAT).

The National Frequency Planning Group (NFPG) is responsible for maintaining the UK FAT. The NFPG updates the tables following proposals from Government Departments and also clears ECC Decisions with implications for the UK’s radio spectrum within government. The NFPG is part of the subordinate committee structure under the Cabinet Official Committee on UK Spectrum Strategy. The National Frequency Assignment Panel (NFAP) operates under the NFPG: it considers requests for frequency assignments and maintains the National Frequency register (NFR). Ofcom provides the secretariat to the committees, updating and maintaining the associated databases.

All frequency assignments registered on the NFR have to be considered by the NFAP. However, this can be a lengthy process and the Panel has recently agreed that, in certain frequency bands where there are no sharing concerns, spectrum may be assigned on the NFR before being discussed at a Panel meeting.

‘Block cleared spectrum’ at January 2005 includes:

<table>
<thead>
<tr>
<th>57.0 – 59.0 GHz</th>
<th>Primary Fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR 5.547 identifies the band for high-density applications. There is primary Mobile allocation but this is not used. There are also co-primary allocations to the EESS (passive) and Space Research (passive) services. In addition, there is a co-primary allocation to the inter-satellite service at 57.0 – 58.2 GHz, the power of which is limited by RR 5.556A, RR 5.556 permits use of sub-band at 58.2-59.0 GHz for Radio Astronomy but this is not used in the UK.</td>
<td></td>
</tr>
</tbody>
</table>
Radio Systems at 60GHz and Above

64.0 – 65.0 GHz
Primary Fixed
RR 5.547 identifies the band for high-density applications in the HDFS. There are also co-primary allocations for the Mobile (except aeronautical mobile) and Inter-Satellite services but these are not used in the UK. RR 5.556 permits use of the sub-band at 64.0 – 65.0 GHz for Radio Astronomy but this is not used in the UK.

65.0 – 66.0 GHz
Primary Fixed
RR 5.547 identifies the band for high-density applications in the HDFS. There are also co-primary allocations for the Mobile (except aeronautical mobile) and Inter-Satellite services but these are not used in the UK. There are also co-primary allocations to the EESS, SR and IS services and decisions taken at WRC-97 to make the 64-66 GHz available for HDFS through RR 5.547 took into account the sharing environment with the EESS, SR and IS services. The Earth Exploration Satellite Service, Space Research and Inter-Satellite services are not using the 64-66 GHz band in the UK.

The UK plays an active role in the ECC/ERO, complies with Decisions and observes Recommendations.

ERC Report 25 - FMWG European Common Allocation Table - may be summarised as follows:

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>Reported utilisations</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>59 - 61</td>
<td>Defence harmonised band</td>
<td>ERC REC T/R 22-03</td>
</tr>
<tr>
<td>61 - 62</td>
<td>Fixed</td>
<td>ERC REC 70-03</td>
</tr>
<tr>
<td>62-63</td>
<td>ISM and SRD</td>
<td>ERC REC T/R 22-03</td>
</tr>
<tr>
<td>63-64</td>
<td>Road traffic</td>
<td>ERC DEC (92) 02</td>
</tr>
<tr>
<td>64-66</td>
<td>Fixed</td>
<td>ERC REC (05) 02 (June 2005)</td>
</tr>
<tr>
<td>66-71</td>
<td>Future civil</td>
<td></td>
</tr>
<tr>
<td>71-76 (81-86)</td>
<td>Future civil (+ defence)</td>
<td>Annex 4 to Doc. SE19 (05) 50 (May 2005)</td>
</tr>
<tr>
<td>76-77,5</td>
<td>Amateur</td>
<td>EN 301 783</td>
</tr>
<tr>
<td>77,5-78</td>
<td>Astronomy</td>
<td>ERC REC (92) 02</td>
</tr>
<tr>
<td>78-81</td>
<td>Radiolocation</td>
<td></td>
</tr>
<tr>
<td>81-86 (71-76)</td>
<td>Future civil (+ defence)</td>
<td>Annex 4 to Doc. SE19 (05) 50 (May 2005)</td>
</tr>
<tr>
<td>86-92</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>92-105</td>
<td>Short range radar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Astronomy</td>
<td>ERC REC (92) 02</td>
</tr>
</tbody>
</table>
Recommendations have been made by SE19 (ECC/ERO) in respect of the bands at 64-66GHz and 71-76 / 81-86GHz. The 64-66GHz recommendation has now been published as (05)02: it is largely based on a work item submitted by the UK. The recommendation gives the guidelines for administrations to consider when implementing their national regulations for fixed services: SE19 did not discuss mobile use. The 71-76/81-86GHz recommendation on FS channel arrangements has also been finalised and was adopted at the last WGSE meeting (6-10 June 05) for public consultation.

ECC Document ECC/REC/(05)02 is attached to this report as Annex 8. Draft ECC Document is attached to this report as Annex 7.

In summary, (05)02 (64-66GHz) states
- band 'opened for use by fixed service (FS) systems in some European countries'
- high density high capacity point-to-point links
- ETSI spec TS 102 329
- very short distance links 'call for a light licensing regime'
- provides example in Annex 2
- recommends administrations choose either
- to allow assignments without a specific channel arrangement
- or use simplified frequency slots as shown in Annex 3
- administrations should define 'suitable safeguards for interference avoidance between adjacent blocks'

And (05)07 (71-76 / 81-86GHz) states
- very high capacity (up to 10 Gbit/s)
- possibility of multiple channel frequency re-use
- 1-2 km hop lengths
- multiple services and applications without interference concerns
- no need for coordination
- recommends that Administrations choose either
- to use whole or parts of the bands with the channel arrangements in Annex 1 and Annex 2 respectively
- or allow systems with 10 GHz duplex separation using blocks from 71-76/81-86 GHz as in Annex 3

It is interesting to note that ECC Recommendation (05)02 states
- that the very short distance links in the 64-66 GHz band call for a light licensing regime;

and
- that the atmospheric attenuation in this band may not be sufficient to ensure that a high density of links can be achieved without suitable management to avoid interference;

whereas Annex 4 to the Draft ECC Recommendation (05)07 states
- that the high frequency reuse achievable with the high gain, low size and high directional pencil-sized beam antennas reduces the requirement for frequency planning techniques and offers the possibility of deregulated telecommunications environment within CEPT countries for various low power, low cost and short range fixed wireless systems;
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This seems to imply that 65GHz needs 'light' regulation and the higher band needs no regulation, based on oxygen absorption and on antenna beam size. In fact the text reflects a drafting compromise: the UK initiated the 64-66GHz work item within CEPT and promoted light licensing which it had already adopted internally. Other CEPT administrations preferred the more traditional licensed approach. Recommendation (05)02 provides guidelines which include an example (based on a UK Ofcom contribution) on how light licensing could be implemented for those administrations wishing to implement light licensing. The final decision lies with the local national administration concerned. The proposed new recommendation on 71-76/81-86GHz addresses only the channel plan for these bands and does not highlight any particular licensing approach.

The 63-64GHz band is also allocated to (RTTT) Road Transport and Telematics also known as Intelligent Transport Systems (ITS) in the ECC Rec 70-03 and UK FAT. Work is ongoing in ETSI/ISO/ITU to define the technical characteristics of the system and the application is being considered for licence exempt use. In addition, the USA, Canada, Australia and Japan have regulations allowing the use of low power licence exempt equipment in the bands up to 66GHz for WPAN applications.

The current work item for SE19 is as follows:

<table>
<thead>
<tr>
<th>SE WP Ref#</th>
<th>Subject</th>
<th>Output</th>
<th>Start/Target dates</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE19_12</td>
<td>FS above 70 GHz</td>
<td>New ECC Rec on frequency arrangements for FS in frequencies above 70 GHz, focusing on 71-76 GHz band</td>
<td>S: May 2004 T: June 2005</td>
<td>Draft ECC Rec approved for public consultation. Liaison sent to WGFM</td>
</tr>
</tbody>
</table>

No further work items have been proposed to date.

Some of the above data was supplied by
Nasarat Ali
Fixed Wireless Services
Ofcom
Direct Line: 020 7981 3126
nasarat.ali@ofcom.org.uk

58
4.3 SURVEY

4.3.1 Process

Questionnaires were issued to regulators, manufacturers, integrators and operators, at three differing levels of complexity.

The first, initial, questionnaire was sent to all European regulators, a sample of non-European regulators, and to a sample of manufacturers and operators. It was designed to establish the correct contacts in the country, and to start the information gathering process, whilst having a limited number of questions as it has been shown in the past that including too many questions reduces the number of responses received. The Questionnaire is shown in Annex 1. The list of recipients is given in Annex 2.

It was resent during March 2005 to the following regulators:

Albania, Belarus, Belgium, Bosnia, Bulgaria, Croatia, Denmark, France, Macedonia, Greece, Hungary, Italy, Latvia, Luxembourg, Malta, Monaco, Poland, Romania, Russia, Slovakia, Slovenia, Spain, Turkey, Ukraine, Vatican.

The initial questionnaire was further distributed to regulators outside Europe during early February 2005. Annex 3 shows the selected countries which were chosen to give a global sampling.

Two follow up questionnaires were then designed, one for regulators and one for industry - these were issued to recipients who indicated a willingness to engage in the process. The final process was in the form of face-to-face and telephone interviews, for which a guidance structure was created. These interviews were held with a representative number of manufacturers and operators.

In addition to the summary and discussion in the Paragraph below, a more detailed summary of the data gathered for the bands at 59,3-66 GHz, 71-76 GHz, 81-86 GHz, and 92-100 GHz is presented in following Annexes. Please note that contact information is only given where the respondent differs from the addressee shown in Annex 2.

4.3.2 European National Regulators

Final allocations of frequencies and the definition of licensing regimes in Europe is devolved to national administrations. There is no simple position, despite all national administrations expressing full support for the ERC process.

Of the 21 replies, only 8 had opened some or all of the bands. Estonia, Lithuania and Finland have opened all the bands, on a fully-licensed basis. Switzerland has opened all the bands currently available in the USA, but on a conventional, fully-licensed basis. Luxembourg has opened 59-66 GHz, again on a fully-licensed basis. The Czech Republic and Slovenia have opened the bands 64-66, 74-76, and 84-86 GHz, on a
Radio Systems at 60GHz and Above

lightly-licensed basis. Norway has opened 64-66 GHz, on the same basis as the USA-FCC (which Norway describes as ‘either exempt or light’).

Germany and Denmark have not opened any bands as yet, but have said that when they do, at least some of the bands will be lightly-licensed. France is reserving its position, pending the outcome of various ERC decisions.

<table>
<thead>
<tr>
<th>Country</th>
<th>Email(s)</th>
<th>Status and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td><a href="mailto:herbert.waxenegger@bmvit.gv.at">herbert.waxenegger@bmvit.gv.at</a></td>
<td>None of the above bands open yet. No decision taken on the licensing approach should they be opened.</td>
</tr>
<tr>
<td>Cyprus</td>
<td><a href="mailto:321925aelia@mcw.gov.cy">321925aelia@mcw.gov.cy</a></td>
<td>No-one has applied, nor has authorisation been given, for 60-100GHz operation. Will review when applications are submitted.</td>
</tr>
<tr>
<td>Czech Republic</td>
<td><a href="mailto:zemanp@ctu.cz">zemanp@ctu.cz</a></td>
<td>64-66 GHz only lightly licensed, 74-76 GHz only lightly licensed, 84-86 GHz only lightly licensed, 92-100 GHz not licensed.</td>
</tr>
<tr>
<td>Denmark</td>
<td><a href="mailto:jtc@itet.dk">jtc@itet.dk</a></td>
<td>None of the bands open yet. If the 65GHz band opens then a light licensing regime is highly possible to be implemented.</td>
</tr>
<tr>
<td>Estonia</td>
<td><a href="mailto:signe.maurus@sa.ee">signe.maurus@sa.ee</a> <a href="mailto:lada.jostina@sa.ee">lada.jostina@sa.ee</a> <a href="http://www.sa.ee">http://www.sa.ee</a></td>
<td>All bands are open for fixed link use, and all are on a fully licensed basis.</td>
</tr>
<tr>
<td>Finland</td>
<td><a href="mailto:kalle.pikkarainen@ficora.fi">kalle.pikkarainen@ficora.fi</a> <a href="http://www.ficora.fi/englanti/radio/Taulukko5.htm">http://www.ficora.fi/englanti/radio/Taulukko5.htm</a></td>
<td>All the bands are open for Fixed Link use, but there is no detailed channel plan. All are fully licensed. Finland follows actively the work of ECC PT SE19.</td>
</tr>
<tr>
<td>France</td>
<td><a href="mailto:bdeschamps@compuserve.com">bdeschamps@compuserve.com</a> <a href="mailto:didier.dubreuil@art-telecom.fr">didier.dubreuil@art-telecom.fr</a> <a href="http://www.art-telecom.fr">www.art-telecom.fr</a></td>
<td>Situation is under review, with a policy expected following SE19 decision. The information will be available on the EFIS web site.</td>
</tr>
<tr>
<td>Germany</td>
<td><a href="mailto:meik.gawron@regtp.de">meik.gawron@regtp.de</a></td>
<td>None of the bands are yet open. Germany will follow presently emerging CEPT recommendations as far as possible. It is preferred that 59.3-66 GHz should be fully licensed. No decision on licensing rules has been taken for the other bands. 59.3-64 GHz: shared civil and military use 64-66 GHz: civil use only 71-75.5 GHz: shared civil and military use 75.5-76 GHz: civil use only 81-84 GHz: military use only 84-86 GHz: civil use only 92-95 GHz: shared civil and military use 95-100 GHz: military use only There are no working groups / operator groups within the country that are active in these bands.</td>
</tr>
<tr>
<td>Hungary</td>
<td></td>
<td>None of the bands are open.</td>
</tr>
<tr>
<td>Country</td>
<td>Email</td>
<td>Details</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Iceland</td>
<td><a href="mailto:gudmundur@pta.is">gudmundur@pta.is</a></td>
<td>None of the bands are open yet. In fact there are no links above 26GHz in operation.</td>
</tr>
<tr>
<td>Ireland</td>
<td><a href="mailto:tara.kavanagh@comreg.ie">tara.kavanagh@comreg.ie</a></td>
<td>None of the above bands are open. Trial licences are being awarded.</td>
</tr>
<tr>
<td>Liechtenstein</td>
<td><a href="mailto:Fari.Hosseini@ak.llv.li">Fari.Hosseini@ak.llv.li</a></td>
<td>'Strategic' bands are: 64-66 GHz fixed point-to-point links; 71-76 GHz fixed point-to-point links; paired with 81-86 GHz; 77-81 GHz UWB automotive SRR; 81-86 GHz fixed point-to-point links; paired with 71-76 GHz; 75.5-76 GHz is allocated to (and used by) amateurs until 2006.</td>
</tr>
<tr>
<td>Lithuania</td>
<td><a href="mailto:mzilinskas@rrt.lt">mzilinskas@rrt.lt</a></td>
<td>All spectrum open except 94.0-94.1 GHz. All bands are lightly licensed.</td>
</tr>
<tr>
<td>Luxembourg</td>
<td><a href="mailto:roland.thurmes@lir.lu">roland.thurmes@lir.lu</a>, <a href="http://www.lir.etat.lu/freq/legal/index.html">http://www.lir.etat.lu/freq/legal/index.html</a>, <a href="http://www.lir.etat.lu/rtte/interfac/index.html">http://www.lir.etat.lu/rtte/interfac/index.html</a></td>
<td>64-66 GHz is already open for fixed links; 59.3-64 GHz will be opened for fixed links at end-2005. 71-76 GHz is not open except 71-74 GHz harmonised NATO. 81-86 GHz is not open except 81-84 GHz harmonised NATO. 92-100 GHz is not open. All open bands are fully licensed. With the exception of the military allocations, there are no operating systems.</td>
</tr>
<tr>
<td>Netherlands</td>
<td><a href="mailto:herman.teinsma@at-ez.nl">herman.teinsma@at-ez.nl</a>, <a href="http://www.at-ez.nl/nfr/">www.at-ez.nl/nfr/</a></td>
<td>None of the bands are open.</td>
</tr>
<tr>
<td>Norway</td>
<td><a href="mailto:stein.gudbjorgsrud@npt.no">stein.gudbjorgsrud@npt.no</a></td>
<td>64-66 GHz open. Currently drafting a text for the band 64-66 GHz. The band will either be licence-exempt or lightly licensed (in practice licence-exempt with possibility of registering base stations for protection). For the other bands the NPT has received no applications. A final decision on which part of the band to allocate for Fixed Links has therefore not been taken.</td>
</tr>
<tr>
<td>Poland</td>
<td><a href="mailto:A.Gawlik@urtip.gov.pl">A.Gawlik@urtip.gov.pl</a>, <a href="mailto:W.Sega@urtip.gov.pl">W.Sega@urtip.gov.pl</a>, <a href="mailto:S.Wilkowski@urtip.gov.pl">S.Wilkowski@urtip.gov.pl</a></td>
<td>New contacts are dealing with the enquiry: reply awaited.</td>
</tr>
<tr>
<td>Portugal</td>
<td><a href="mailto:luisa.mendes@anacom.pt">luisa.mendes@anacom.pt</a></td>
<td>None of the above bands open.</td>
</tr>
<tr>
<td>Sweden</td>
<td><a href="mailto:christiansallstrom@ots.se">christiansallstrom@ots.se</a></td>
<td>No bands or part bands have been opened.</td>
</tr>
</tbody>
</table>
Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Country</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slovenia</td>
<td>64-66 GHz is open, lightly licensed. It is planned to open 74-76 GHz and 84-86 GHz, also on a lightly licensed basis. T/R 22-03 is followed. The national entry on <a href="http://www.efis.dk/search/general">www.efis.dk/search/general</a> is not up to date.</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Frequencies 59.3-62 GHz, 64-66 GHz, 71-76 GHz, 81-86 GHz, 92-94 GHz, 94.1-100 GHz are open. All of these bands are Fully Licensed, due to sharing with military.</td>
</tr>
</tbody>
</table>

4.3.3 Non-European National Regulators

In the USA, the Federal Communications Commission (FCC) have made rules for the 57-64GHz, 71-76 GHz, 81-86 GHz and 92-95 GHz bands. These rules use a nonexclusive licensing approach which is intended to provide interference protection from the date that licensees register on a link-by-link basis in a national database. Traditional frequency coordination between users will not be required of licensees.

The FCC rule making was initiated by a petition from Loea Communications, Hawaii, for the establishment of service rules for the licensed 71-76 GHz and 81-86 GHz bands. The rule making was also supported by more than a dozen leading organisations such as Cisco, Harris, Andrews, Stratex Networks, Ceragon Networks, Wireless Communications Association (WCA) and the Fixed Wireless Communications Coalition (FWCC).

The FCC also permits unlicensed, indoor use of the 92.0-94.0 GHz and 94.1-95.0 GHz bands by non-federal government users. This unlicensed indoor use will be governed by Part 15 of the FCC’s rules and will be based on existing regulations for the 57-64 GHz band. The FCC have not authorised unlicensed use of the 71-76 GHz and 81-86 GHz bands.

A complete history of the 71-76 and 81-86 GHz filings can be found on the FCC’s Millimetre Wave 70-80-90 GHz Service website at http://wireless.fcc.gov/services/millimeterwave.

Canada is fully harmonised with the USA, and has adopted all the same bands, with the same technical specifications and licensing regime.

Japan has opened band 59-66 GHz is available for unlicensed use.

Australia has opened band 59.4-62.9 GHz on a licensed basis (Radiocommunications Class Licence 2000).

Singapore and Zambia have not opened any bands as yet, but will respond to market demand.

All other recipients of the questionnaire are considering their responses.
Radio Systems at 60GHz and Above

Taiwan
Ching-Chich Lin (Mr.)
Acknowledgement only at this stage.
Enquiry has been referred to the relevant department; further information is promised.

Zambia
kmasiye@caz.gov.zm
All the bands in question are at the moment free. No operator has asked for spectrum in these bands.

Philippines
General frequency clearances and/or assignment is done by Frequency Management Division: fmd@ntc.gov.ph
but licensing is done by various units:
1. Radio Regulations and Licensing Department for private networks, aeronautical services and maritime services: rrl@ntc.gov.ph
2. Common Carrier Authorization Department for common carrier services: ccad@ntc.gov.ph
3. Broadcast Services Department: bsd@ntc.gov.ph

Israel
benbassatm@moc.gov.il
Basat is responsible for telecommunications services, including Bezeq services, international services and cellular telephony.

Canada
http://www.ic.gc.ca/cmb/welcomeic.nsf/ICPages/ContactUs
Policy is determined by Industry Canada.
This is also the government department responsible for the technical standards of telecommunication and radiocommunication equipment.
Fully harmonised with USA (which see).

Japan
ikeda637@oki.com
Band 59-66 GHz is available for unlicensed use, with the following specification:
- Maximum output power is 10 mW
- Maximum antenna gain is 47 dBi
- Frequency stability within +/-500 ppm
- Maximum Bandwidth is 2.5 GHz

Singapore
teo_geok_hoon@ida.gov.sg
Bands unoccupied.
IDA welcomes applications for trials.
Bands will be opened once there is demand.

Australia
59.4 GHz to 62.9 GHz
Radiocommunications Class Licence 2000.
Output Power
(i) 10 mW (+10 dBm) maximum total peak transmitter power into the antenna
(ii) 150 W (+51.8 dBm) peak maximum EIRP

USA
57-64GHz open on a lightly licensed basis.
71-76GHz, 81-86 GHz and 92-95 GHz now open using web-based Link Registration System. Process takes 10 minutes and costs USD100 for 10 years. Registration gives interference protection.
IEEE 802.15 has been set up to create standards for Wireless Personal Area Networks (WPANs). Within 802.15, task group 802.15.3c is charged with creating a standard for the physical layer at 57 to 64GHz in response to the USA-FCC’s allocation of a licence-exempt allocation in that band. The group is thought to be about two years from a standard.

The graphic below is taken from ‘Understanding UWB - Principles & Implications for Low-Power Communications,’ submission to IEEE802.15 Working Group for Wireless Personal Area Networks, Doc. IEEE802.15-03/157r1, March 2003. It was based on work by R. Aiello, J. Ellis, U. Kareev, K. Siwiak, and L. Taylor.

The targets for 802.15.3c include:

- Bit Rate and Range - More than 1Gbps@10m
- uncomplicated coexistence with other 802 systems (TG3a, Bluetooth, etc)
- operate with the 802.15.3 MAC without fundamental changes.
- simple spectrum mask
- robust indoor multipath
- frequency stability within +/-500ppm
- simple signal processing
- Power Output by comparison with TG3a Alt-PHY Technical Requirements
  - 100mW or less @100Mbps
  - 250mW or less @200Mbps
  - Power save function

4.3.5 Industry

The high data rates associated with the frequencies above 60GHz are primarily targeted for use by carriers as a fibre alternative. The applications include short hops, base
station backhaul, fibre bridging, ultra-high capacity access, storage area networks and data centres. The target deliverable bandwidths for these applications are between 1 and 10Gb/s over distances up to 2km. The primary driver for installing such a radio network would be the very high cost or difficulty of installing a fibre network.

Currently this high Gb/s capacity requirement cannot be gained by utilising the lower frequencies due to the regulatory controls and spectrum availability.

One of the key drivers in the take up of Gb/s radios will be the procurement pricing. Products at this frequency see high manufacturing cost increases as the modulation scheme increases. High order modulations such as 64/128QAM are expensive to produce and significantly reduce the transmission path length. Adaptive modulation schemes which will help manage the transmission path length are possible but extremely expensive. Lower order modulation schemes such as QPSK and BPSK are more spectrum hungry but permit lower product manufacturing costs.

Channel sizing is an issue at these bands. There is widespread support for the adoption of 250MHz channels and allowing up to 5 to be grouped. The consensus view of commercial respondents is that in the bands 57-64GHz and 71-76/81-86GHz, a lightly licensed approach should be adopted, with effective permission being given for up to the full nineteen 250MHz channels to be used by a single radio. Spectral efficiency will be driven by the increased licence costs proportional to the number of 250 MHz channels used. These channels are as noted in the ECC Document ECC/REC/(05)07.

Operators are now starting to deploy high frequency networks. Some examples are given below:

- September 30, 2005 - GigaBeam Corporation announces that it has signed an agreement with Eaton and Associates for the sale of 1 Gigabit WiFiber™ wireless fibre links for the City of San Francisco Public Utilities Commission (PUC) as part of their first phase of planned deployments to enable live video, data and voice over IP (VoIP) communications. The Radios operate in the 71-76 GHz and 81-86 GHz radio spectrum bands.

- 01/04/05 - TESSCO awarded GSA Schedule to supply BridgeWave 60GHz products to city, county, state and Federal government entities.

- September 21, 2005 - American IP has installed GigaBeam 71-76 GHz radios for CompuCredit Corporation as an alternative communications link to back up existing terrestrial fibre.

- Terabeam Corporation, 2003 announced today that OnFiber is use Terabeam’s Gigalink™ gigabit Ethernet (GigE) wireless fibre system to extend its fibre optic network to serve additional customers. The GigE Gigalink provides OnFiber the ability to provide alternative connectivity options to its existing customer base as well as expand its network reach. Currently, OnFiber operates fibre optic networks in 14 major metropolitan areas throughout the U.S. Terabeam’s GigE Gigalink is the first radio frequency (RF) product certified by the FCC that provides full duplex
Gigabit line rates. The GigE Gilalink provides an interface to a customer’s communications network that transmits and receives signals at 1.25 gigabits per second (Gbps), Global Infrastructure and Telecommunications Institute, Waseda University Japan, 60GHz campus Links.
4.4 DISCUSSION

Expected applications for systems using the bands between 60 and 100GHz include high-speed wireless local area networks, broadband wireless access systems for the internet, point-to-point links and point-to-multipoint configurations.

The technology will in effect be equivalent to fibre-optic cables, filling gaps in current fibre-optic networks in rural areas and inner cities where the cost of digging to lay cables inhibits growth. Nevertheless, range is weather-limited to the order of a few kilometres. The most typical application will perhaps be a campus setting where buildings have not yet been connected to fibre.

Frequencies in the range 59.3-66 GHz have been allocated in Europe, USA and Japan, with Latam, Africa and most of Asia-Pacific likely to follow suit. The allocations at 71-76/81-86 GHz in the USA are in the process of being copied in Europe, though with important differences of specification and licensing. The 92-95 GHz band is currently only open in the USA. The consensus industry view is that the current USA regulations favour market acceptance and promote competition; there are some concerns about the European position.

A typical industry response is that provided by Dr Johnathon Wells of Gigabeam. Gigabeam join with past-Chairman Powell of the USA-FCC in believing that the USA rule-making encourages early and spectrally efficient deployment in the bands above 57GHz.

This is because:
- The spectrum is regulated under FCC Part 101 rules, the same rules governing all existing FS equipment in the USA.
- The two 5 GHz channels (at 71-76/81-86GHz) are regulated to enable cost effective gigabit and multi-gigabit FS equipment operating at distances of 1-2 kms with 99.999% weather availability.
- A ‘light touch’ licensing scheme was created, whereby internet based coordination and approval can be usually achieved in less than 30 minutes for around €100 per license.

Together the 71-76 and 81-86 GHz allocation has enabled a wide range of new wireless products and services to be introduced in the USA. Gigabit Ethernet radios operating at 1.25 Gbps are freely available, offering transmission over distances of over a kilometre with availability statistics that cannot be matched by any alternative wireless technologies. By 2006, the first 10 Gbps FS radios will become available, seriously threatening fibre as the high capacity transmission medium of choice.

ECC/Rec/(05)07 identifies the need for above 70 GHz fixed links to provide 1-10 Gbit/s broadband services over distances of 1-2 km for applications where fibre optic cables are not cost-effective. The document acknowledges that this multi-gigabit capacity cannot be served by lower frequencies due to their relatively narrow channel bandwidths.
Industry believes that the key driver for this target market is product price. To compete effectively with fibre, which is prevalent throughout Europe and the rest of the developed world, products need to be low cost and easy to install and maintain. Low modulation complexity products (e.g. FSK or QPSK) will dominate over more complex radio products. The simpler architectures of lower complexity modulation radios will result in lower cost and higher reliability products. Such products will also benefit from improved performance due to transmitters operating with higher powers (less power amplifier back-off) and with improved receiver sensitivities (lower receiver C/N) allowing larger fade margins to be achieved and longer link distances to be realized.

One possible competitor to millimetre-wave FS and WPAN is Ultra-Wideband (UWB). MW-FS/WPAN offer Gigabit speeds. However, they are affected by the well-known propagation characteristics, and are both line-of-sight and weather-dependent. In this respect they have certain similarities to infra-red communication (standard IRDA), which has not competed successfully with Bluetooth. It is possible that UWB will become the non-line-of-sight technology for Gigabit personal area networking, and MW-FS/WPAN would play the role of ‘fast IRDA’.

Nevertheless, MW-FS/WPAN has several advantages compared to UWB:

- No interference to other systems because of large frequency difference
- Good coexistence because of path-loss
- Antenna directivity (UWB may be not allowed to use high gain antennas)
- Simple modulation/demodulation (Spread spectrum schemes are essential for UWB)
- Simple signal processing (For UWB, complex technologies such as rake-receiver, or high frequency A/D, D/A converter and DSP will be needed for signal processing)
- Higher speed transmission (more than 1Gbps)

A further consensus is in support of the ‘Spectrum Commons’ concept for high frequencies. This could be managed on a ‘light licensed’ basis in the manner adopted by the USA-FCC. The thesis is well made by Dr. Daniel Kelley in ‘Economically Efficient Licensing of the Millimetre Wave Band’. This argues that link licensing is advantageous over spectrum auctions for a competitive and efficient market at these frequencies.
4.5 CONCLUSIONS AND RECOMMENDATIONS

4.5.1 Market readiness and applications

The high data rates associated with the frequencies above 60GHz are primarily targeted for use with carriers for fibre alternatives. Declared applications for these include:

- Short alternative fibre hops - Last Mile Access and Infrastructure
- Metropolitan Area Networks - Redundancy, Network Expansion or Private Networks
- Campus Area Networks - Hospitals, Schools, Military Bases, or Enterprises
- Base station backhaul - WiMax, WiFi, Cell Antenna Extension, etc
- Fibre bridging
- Temporary Bandwidth - Disaster Recovery, Network Expansion
- Storage links

Manufacturers are now launching useable product, especially near the oxygen peak at 60GHz. These products exploit USA-FCC rules and provide a range of typically 1km. There is also some activity at higher frequencies with longer range but manufacturers are waiting for orders before committing to production tooling. European and other regulators are starting to respond, although the response is far from uniform, e.g. between Europe, USA, and ROW. Within Europe some regulators are establishing national regimes, but most have waited for the report of SE-19 (just available as this interim report was in preparation). There is still a preponderance of formal licensing, but some regulators will adopt a mix of unlicensed and lightly licensed processes.

4.5.2 Technical regulatory parameters

The following interim recommendations represent the consensus view of commercial respondents. The conclusions and recommendations of the team on the current project are presented in Paragraph 2 of this report.

Manufacturing industry (most active respondents are USA-based) and potential importers/integrators and users recommend that the ECC should facilitate and encourage simple architecture products wherever possible. They state that this will allow cost effective products to be developed to satisfy the identified market requirements; equipment of this kind is already available from the USA.

TPC

To provide an element of international standardisation and to encourage market growth and product availability, TPC should not be mandatory in the bands 64-66GHz, 71-76GHz and 82-86GHz.
Channel sizes

Due to the nature of the applications and the directivity of operational equipment in these bands, there should be no restriction on channel size. 10GB/s radio links would require the full 5GHz spectrum.

This is currently the case with the USA-FCC part 1010 which at 71-76 / 81-86GHz allows operators to use the full 5GHz and has no defined channels. Similarly, the ETSI TS 102 329 (64-66GHz for HDFS) permits links to operate in and across the entire 2GHz band.

The removal of channelisation in the USA is currently viewed as being a successful move by a number of the USA stakeholders.

The USA-FCC has stated:
'We are convinced that elimination of the segmentation scheme will provide manufacturers the freedom to produce radios utilizing a variety of modulation schemes … thus lowering the cost of equipment for new entrants and spurring technological development and rollout. Furthermore, we find that allowing users the maximum flexibility in link design and the freedom to upgrade as their needs evolve will facilitate new entry in this nascent service.'

(Allocations and Service Rules for the 71-76 GHz, 81-86 GHz, and 92-95 GHz Bands, FCC Memorandum Opinion and Order 05-45, March 2005)

Maximum Power output (EIRP)
In order to obtain the QoS required for the delivery of the identified applications, the consensus view is that the power levels given in annex 4 of the Draft ECC Document ECC/REC/(05)07 ‘Radio Frequency Channel Arrangements for Fixed Service System’ should be increased.

As shown below in the description of the trial of commercial equipment, the EIRP limits of ECC/REC/(05)07 are not adequate for the delivery of services up to 2km distance at 99.999% availability in the bands 71-76GHz and 81-86GHz.

The consensus view is that the limits in table A4.3 (shown in Annex 8 of this paragraph) are increased to 19dBm for power at the antenna port for 1Gb FSK links in both the 71-76GHz and 81-86GHz bands, and the limits in table A4.2 for 1Gb 16QAM links be increased to 14dBm in both the 71-76GHz and 81-86GHz bands.

Modulation requirements
There should be no modulation requirements or restrictions. It is believed that BPSK/QPSK will be used in the majority of links due to the link length requirements.
4.5.3 Operating frequencies

As before, the following interim recommendations represent the consensus view of commercial respondents. The conclusions and recommendations of the team on the current project are presented in Paragraph 4.2 of this report.

To satisfy QoS requirements for the identified applications and to provide the required channel bandwidths, the following bands should be opened:

- Bands 59-66 GHz (57-59GHz has already been ‘block cleared’)
- Bands 71-76 GHz
- Bands 81-86 GHz
- Bands 92-100 GHz

4.5.4 Licensing

Deployment of systems at high data rates of 1Gbps and above will not take place if there is significant risk of interference. Nevertheless, these bands are ideally suited to a ‘spectrum commons’ approach: this is most likely to encourage innovative deployments and to maximise spectrum efficiency. Therefore, all the above bands should be opened on a ‘Lightly Licensed’ basis, perhaps adopting the USA-FCC licensing technique.

4.5.5 Further Work

The supply and operation of radio systems in the bands between 60 and 100 GHz is an emerging market, with some very active participants, but it is far from mature. Several vendors are making significant investments and operators are now installing viable networks. However, the regulatory position is very confused, with wide differences in allocated bands, channelisation, permitted power levels and licensing regimes between different administrations. Even within Europe, there is wide divergence: some regulators are following the lead of the USA-FCC, others are waiting for a consensus to emerge from the ERC, whilst others do not see a need at these frequencies.

This unclear situation must impact on the willingness of European manufacturers to invest in full scale production tooling, and is also likely to delay the development of networks by multinational operators (although local small scale operators are already importing USA-sourced equipment where allowed).

The European high frequency radio market has long suffered from a circularity of process:

limited demand - delayed regulatory response - limited investment - limited demand

It is recommended that Ofcom maintain an ongoing interest in the development of a Europe-wide regulatory regime in the frequency bands between 60 and 100GHz that is sympathetic to the needs of both operators and manufacturers. And that the
Radio Systems at 60GHz and Above

development of both regulations and market is continuously monitored throughout 2006.
Annex 1: Initial questionnaire

<table>
<thead>
<tr>
<th>Questions</th>
<th>59.3 – 66 GHz</th>
<th>71 – 76 GHz</th>
<th>81 – 86 GHz</th>
<th>92 – 100 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Does your national entry on the ERO website (<a href="http://www.efis.dk/search/general">www.efis.dk/search/general</a>) give current data?</td>
<td>yes/no</td>
<td>yes/no</td>
<td>yes/no</td>
<td>yes/no</td>
</tr>
<tr>
<td>2 Please indicate if the following bands (or parts of bands) are open for use for Fixed Links</td>
<td>yes/no</td>
<td>yes/no</td>
<td>yes/no</td>
<td>yes/no</td>
</tr>
<tr>
<td>3 If the bands are open, are they a) Licence-exempt b) Lightly licensed c) Fully licensed</td>
<td>a) Licence-exempt b) Lightly licensed c) Fully licensed</td>
<td>a) Licence-exempt b) Lightly licensed c) Fully licensed</td>
<td>a) Licence-exempt b) Lightly licensed c) Fully licensed</td>
<td>a) Licence-exempt b) Lightly licensed c) Fully licensed</td>
</tr>
<tr>
<td>4 Is there a web address where more information is available?</td>
<td><a href="http://www">www</a>. ...........</td>
<td><a href="http://www">www</a>. ........</td>
<td><a href="http://www">www</a>. ........</td>
<td><a href="http://www">www</a>. ........</td>
</tr>
<tr>
<td>5 Please note any specific guidance or national interface documents / specifications that are relevant for operation in these bands.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Are there any working groups / operator groups within your country that are active in these bands? If so please advise any contact details if possible.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Annex 2: Target Recipients of Initial Questionnaire

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<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Email Address</th>
<th>Tel Number</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Country</td>
<td>Name</td>
<td>Email</td>
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</tr>
<tr>
<td>Vatican City</td>
<td>Constantino PACIFIC</td>
<td><a href="mailto:dirteckt@vatiradio.va">dirteckt@vatiradio.va</a></td>
<td>+39 06 6988 43 08</td>
</tr>
</tbody>
</table>
Annex 3: Further distribution of initial questionnaire

The following countries were contacted commencing February 2005.

- **Australia - Australian Communications Authority (ACA)**  
  http://www.aca.gov.au
- **Canada - Canadian Radio Television and Telecommunications Commission**  
  http://www.crtc.gc.ca/eng/welcome.htm
- **Israel - Ministry of Communications**  
  http://www.moc.gov.il/
- **Jordan - Telecommunication Regulatory Commission**  
  http://www.trc.gov.jo/
- **Mexico - Comisión Federal de Telecomunicaciones**  
  http://www.cft.gob.mx/
- **Nepal - Nepal Telecommunications Authority**  
  http://www.nta.gov.np/
- **Philippines - National Telecommunications Commission (NTC)**  
  http://ntc.gov.ph/
- **Singapore - Infocomm Development Authority of Singapore**  
  http://www.ida.gov.sg/
- **Sri Lanka - Telecommunications Regulatory Commission**  
  http://www.trc.gov.lk/
- **Taiwan - The Directorate General of Telecommunications**  
  http://www.dgt.gov.tw/
- **USA - Federal Communications Commission (FCC)**  
  http://www.fcc.gov/
- **Zambia - Communications Authority**  
  http://caz.gov.zm/
Annex 4: Second Stage Questionnaires

Two questionnaires were used; one for manufacturers and integrators, and one for operators. The questionnaires were sent only to selected respondents to the initial questionnaire.
Survey to Manufacturers and Integrators (Confidential)

Dear xxxxxxxxxxxxxx

Sinon Ltd is part of a consortium engaged by Ofcom, the UK radiocomms regulator, which has been charged with investigating existing and future use of the frequency bands between 60GHz and 100GHz allocated to the Fixed Service by the ITU.

We would be grateful if you could help us by answering the questions below and emailing back.

An MS Word copy of the questions is also attached.

If this has been sent to the wrong department within your organisation, please could you advise us whom to contact.

Thank you for your help.

XXXXXXXXXXXX

XXXXXXXXXXX

XXXXXXXXX
### Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Item</th>
<th>59.3 – 66 GHz</th>
<th>71 – 76 GHz</th>
<th>81 – 86 GHz</th>
<th>92 – 100 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Growth</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Can you identify any specific countries that have licensed these bands?</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Are there any countries within the above where the regulatory regime is not helpful to the market?</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>In what way could the situation be improved?</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Do you favour a licensed or unlicensed approach?</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Please identify any barriers that are affecting market growth for your product.</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Your regulatory recommendations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Please quantify any boundary conditions and limitations that should be incorporated in any new licensing of the above bands, from the following list:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max power output (EIRP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Should TPC be required?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Should there be channel size restrictions? If so what? (MHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What modulations should be allowed?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Should there be any spectral efficiency requirement? If so, what? (bits/Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Deployments</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Are there any reference deployments that you can identify? (Countries)</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
<td>&lt;Comment&gt;</td>
</tr>
<tr>
<td>Are you aware of any power level regulations in these countries?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPC requirements?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel size restrictions?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowed modulations?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral efficiency limits?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Radio Systems at 60GHz and Above
Survey to Operators/Potential Operators (Confidential)

Dear xxxxxxxxxxxxxxxx

Sinon Ltd is part of a consortium engaged by Ofcom, the UK radiocomms regulator, which has been charged with investigating existing and future use of the frequency bands between 60GHz and 100GHz allocated to the Fixed Service by the ITU.

We would be grateful if you could help us by answering the questions below and emailing back.

An MS Word copy of the questions is also attached.

If this has been sent to the wrong department within your organisation, please could you advise us whom to contact.

Thank you for your help.

Xxxx

XXXXXXXXXXX

xxxxx

<table>
<thead>
<tr>
<th>Item</th>
<th>59.3 – 66 GHz</th>
<th>71 – 76 GHz</th>
<th>81 – 86 GHz</th>
<th>92 – 100 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please say if you have an interest in using any of these frequency bands for high capacity short haul links in the future.</td>
<td>&lt;Y/N&gt;</td>
<td>&lt;Y/N&gt;</td>
<td>&lt;Y/N&gt;</td>
<td>&lt;Y/N&gt;</td>
</tr>
<tr>
<td>Which year and quarter would you wish to start deployment?</td>
<td>&lt;date&gt;</td>
<td>&lt;date&gt;</td>
<td>&lt;date&gt;</td>
<td>&lt;date&gt;</td>
</tr>
<tr>
<td>In each of these bands do you have a preference for a licensed or unlicensed regulatory approach?</td>
<td>&lt;licensed/ unlicensed&gt;</td>
<td>&lt;licensed/ unlicensed&gt;</td>
<td>&lt;licensed/ unlicensed&gt;</td>
<td>&lt;licensed/ unlicensed&gt;</td>
</tr>
<tr>
<td>Are there any non-regulatory issues which are hindering the growth of FWA in these bands?</td>
<td>&lt;comment&gt;</td>
<td>&lt;comment&gt;</td>
<td>&lt;comment&gt;</td>
<td>&lt;comment&gt;</td>
</tr>
</tbody>
</table>
## Annex 5: Regulators for possible Further Work

<table>
<thead>
<tr>
<th>Country</th>
<th>Regulator Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>Secretaria de Comunicaciones</td>
<td>Argentinean telecoms regulator, site is only available in Spanish</td>
</tr>
<tr>
<td>Bahrain</td>
<td>Telecommunications Regulatory Authority (TRA)</td>
<td>Bahrain - The Telecommunications Regulatory Authority is an independent body, and awards licences to operate, and use radio spectrum.</td>
</tr>
<tr>
<td>Bolivia</td>
<td>Superintendencia de Telecomunicaciones (SITTEL)</td>
<td>Bolivia's telecoms regulator, the site is only available in Spanish</td>
</tr>
<tr>
<td>Botswana</td>
<td>Botswana Telecommunications Authority</td>
<td>Telecommunication authority for Botswana, Southern Africa. Authority for fixed telephony, mobile telephony, broadcasting, Internet, radio, and satellite communications.</td>
</tr>
<tr>
<td>Brazil</td>
<td>ANATEL</td>
<td>Brazil's telecoms regulator press releases, English version.</td>
</tr>
<tr>
<td>Brunei</td>
<td>Jabatan Telekom</td>
<td>Telecoms regulator for Brunei Darussalam. Is currently part of the state owned land line network, but is due to be separated prior to privatisation.</td>
</tr>
<tr>
<td>Burkia Faso</td>
<td>Direction g_ rale de l'Office National des t communications (ONATEL)</td>
<td>State regulator - also operates the telecoms networks - site in French only</td>
</tr>
<tr>
<td>Chad</td>
<td>Minist• de Postes et T•communications</td>
<td>Government regulator, very little information on the site. Site in French only</td>
</tr>
<tr>
<td>Chile</td>
<td>Subsecretaria de Telecomunicaciones (SUBTEL)</td>
<td>Chile's telecoms regulator</td>
</tr>
<tr>
<td>Columbia</td>
<td>Comisi e Regulaci e Telecomunicaciones</td>
<td>Columbia telecoms regulator, only available in Spanish</td>
</tr>
<tr>
<td>El Salvador</td>
<td>Superintendencia General de Electricidad y Telecomunicaciones</td>
<td>El Salvador's telecoms regulator. Site available in Spanish only.</td>
</tr>
<tr>
<td>Egypt</td>
<td>Telecommunications Regulatory Authority (TRA)</td>
<td>Local regulator - site in both Arabic and English</td>
</tr>
<tr>
<td>Georgia</td>
<td>Georgia - Ministry of Posts and Telecommunications</td>
<td>Georgia's telecoms regulator, part of the government.</td>
</tr>
<tr>
<td>Grenada</td>
<td>ECTEL Eastern Caribbean Telecommunications Authority</td>
<td>Eastern Caribbean Telecommunications Authority is the telecommunications regulator for five Eastern Caribbean states.</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Office of the Telecommunications Authority (OFTA)</td>
<td>Telecoms regulator for Hong Kong - available in English and Chinese</td>
</tr>
<tr>
<td>India</td>
<td>Telecom Regulatory Authority of India (TRA)</td>
<td>Government department, responsible for landline and wireless telecoms. Site in English only</td>
</tr>
<tr>
<td>Iran</td>
<td>Islamic Republic of Iran Broadcasting</td>
<td>Government department that oversees telecoms regulation. Site is available in Farsi with some English news</td>
</tr>
<tr>
<td>Jabatan Telekom</td>
<td>Jabatan Telekom Brunei</td>
<td>Telecoms regulator for Brunei Darussalam.</td>
</tr>
<tr>
<td>Country</td>
<td>Agency/Website</td>
<td>Details</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Brunei</td>
<td>- <a href="http://www.telecom.gov.bn/">http://www.telecom.gov.bn/</a></td>
<td>Features information on services and regulations as well as forms and contact information.</td>
</tr>
<tr>
<td>Kenya</td>
<td>Communications Commission of Kenya</td>
<td>Established in 1998 - site in English only.</td>
</tr>
<tr>
<td>Korea</td>
<td>Ministry of Communications and Informations</td>
<td>South Korean government department. Responsible for all digital communications and media. Site in Korean, Chinese and English.</td>
</tr>
<tr>
<td>Lebanon</td>
<td>Ministry Of Telecommunications</td>
<td>Lebanese government department responsible for telecoms regulation. Site is available in Arabic and English.</td>
</tr>
<tr>
<td>Macau</td>
<td>Office for the Development of Telecommunications and Information Technology</td>
<td>Telecoms regulator for Macau - available in Chinese, Portuguese and English.</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Communications and Multimedia Commission (MCMC)</td>
<td>Government linked department responsible for telecommunications - site mainly in English.</td>
</tr>
<tr>
<td>Mali</td>
<td>Société des Técommunications du Mali (StTM)</td>
<td>National operator - site availability is erratic.</td>
</tr>
<tr>
<td>Mauritania</td>
<td>Office des Postes et Télécommunications</td>
<td>National regulator - site in French only.</td>
</tr>
<tr>
<td>Mauritius</td>
<td>The Ministry of Information Technology and Telecommunications</td>
<td>Government department that is responsible for telecoms regulation.</td>
</tr>
<tr>
<td>Mongolia</td>
<td>Post and Telecommunications Authority of Mongolia, <a href="http://www.pta.gov.mn">http://www.pta.gov.mn</a></td>
<td>Implementation Agency of Mongolian government, Post and Telecommunication Authority is the policy making, project planning and executing agency for the nationwide information and communication infrastructure development.</td>
</tr>
<tr>
<td>Morocco</td>
<td>National Agency for the Regulation of Telecommunications (ANRT)</td>
<td>Recently created independent telecoms regulator in Morocco. Site is mainly in French and Arabic, but some English also.</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Commerce Commission of New Zealand, Nigerian Communications Commission</td>
<td>Government department that also manages telecoms regulation - site in English only with some pages still under construction.</td>
</tr>
<tr>
<td>Nigeria</td>
<td></td>
<td>PTA was formed under the Pakistan Telecommunication Reorganization Act, 1996 - site only available in English.</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Pakistan Telecommunications Authority</td>
<td>Papua New Guinea telecoms regulator - looks after telecoms, radio, tv, and amateur radio hams.</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>PANGTEL</td>
<td>Paraguayan telecoms regulator - only available in Spanish.</td>
</tr>
<tr>
<td>Paraguay</td>
<td>Conatel, telecoms regulator</td>
<td>Eastern Caribbean Telecommunications Authority is the telecommunications regulator for five Eastern Caribbean states.</td>
</tr>
<tr>
<td>Saint Lucia</td>
<td>ECTEL Eastern Caribbean Telecommunications Authority</td>
<td>Eastern Caribbean Telecommunications Authority is the telecommunications regulator for five Eastern Caribbean states.</td>
</tr>
<tr>
<td>Saint Vincent and the Grenadines</td>
<td>ECTEL Eastern Caribbean Telecommunications Authority</td>
<td>Eastern Caribbean Telecommunications Authority is the telecommunications regulator for five Eastern Caribbean states.</td>
</tr>
<tr>
<td>San Marino</td>
<td>Segereteria di Stato per l'Industria, l'Artigianato, la Cooperazione economica, le Poste e le Telecomunicazione</td>
<td>San Marino's telecoms regulator. Site in Italian only.</td>
</tr>
<tr>
<td>Singapore</td>
<td>Infocom Development Authority of Singapore</td>
<td>Telecoms regulator for Singapore.</td>
</tr>
<tr>
<td>South Africa</td>
<td>ICASA</td>
<td>The Independent Communications Authority of South Africa was established in July 2000. It took</td>
</tr>
</tbody>
</table>
Radio Systems at 60GHz and Above

over the functions of the South African Telecommunications Regulatory Authority (SATRA)
Annex 6: United Kingdom Frequency Allocation Table 2004

Issue No. 13

**Key:**

<table>
<thead>
<tr>
<th>ITU FREQUENCY BAND</th>
<th>ITU PRIMARY ALLOCATION (1)</th>
<th>ITU PRIMARY ALLOCATION (2)</th>
<th>ITU Secondary Allocation (1)</th>
<th>ITU Secondary Allocation (2)</th>
<th>UK specific allocations, where made</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.3-64.0 GHz</td>
<td>INTER-SATELLITE</td>
<td>FIXED</td>
<td>RADIOLOCATION</td>
<td>INTER-SATELLITE</td>
<td>FIXED except aeronautical mobile</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EARTH EXPLORATION-SATELLITE</td>
</tr>
<tr>
<td>64.0-65.0 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>INTER-SATELLITE</td>
</tr>
<tr>
<td>65.0-66.0 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EARTH EXPLORATION-SATELLITE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>INTER-SATELLITE</td>
</tr>
</tbody>
</table>

59.3-64.0 GHz – Ofcom (for the Fixed service) and MoD (for the Mobile and Radiolocation services)

63-64 GHz shared with RTTT devices
### Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Fixed Use</th>
<th>Mobile Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.0-74.0 GHz</td>
<td>FIXED</td>
<td>MOBILE</td>
</tr>
<tr>
<td>74.0-75.5 GHz</td>
<td>FIXED</td>
<td>MOBILE</td>
</tr>
<tr>
<td>75.5-76.0 GHz</td>
<td>FIXED</td>
<td>MOBILE</td>
</tr>
<tr>
<td>76.0-77.5 GHz</td>
<td>FIXED</td>
<td>MOBILE</td>
</tr>
</tbody>
</table>

**Fixed Use:**
- FIXED: Broadband-Broadcasting
- FIXED-SATELLITE (Earth to space): Broadcasting-Satellite
- MOBILE: Amateur
- MOBILE-SATELLITE (Earth to space): Fixed-Satellite (space to Earth)
- MOBILE-SATELLITE (space to Earth): Space Research (space to Earth)

**Mobile Use:**
- MOBILE: Amateur-satellite
- MOBILE: Space Research (space to Earth)

---

*Ofcom for the Fixed and Mobile services*  
*MoD for the Fixed-Satellite and Mobile-Satellite services*  
*Amateur and Amateur-Satellite use until 31 December 2006*  
*76-77 GHz shared with RTTT devices*  
*Ofcom for civil Radiolocation including RTTT*
### Radio Systems at 60GHz and Above

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>77.5-78.0 GHz</td>
<td>AMATEUR</td>
</tr>
<tr>
<td></td>
<td>AMATEUR-SATELLITE</td>
</tr>
<tr>
<td></td>
<td>RADIOLOCATION UK5</td>
</tr>
<tr>
<td></td>
<td>Radio Astronomy</td>
</tr>
<tr>
<td></td>
<td>Space Research (space to Earth)</td>
</tr>
<tr>
<td>76-78 GHz; Ofcom for civil Radiolocation including RTT</td>
<td>78-79 GHz; Ofcom &amp; MoD for civil/military Radio location</td>
</tr>
<tr>
<td>79-81 GHz</td>
<td>RADIO ASTRONOMY</td>
</tr>
<tr>
<td></td>
<td>RADIOLOCATION</td>
</tr>
<tr>
<td></td>
<td>Amateur</td>
</tr>
<tr>
<td></td>
<td>Amateur satellite</td>
</tr>
<tr>
<td></td>
<td>Space Research (space to Earth)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>84.0-86.0 GHz</td>
<td>FIXED</td>
</tr>
<tr>
<td></td>
<td>FIXED-SATELLITE (Earth-to-space)</td>
</tr>
<tr>
<td></td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td>RADIOASTRONOMY</td>
</tr>
</tbody>
</table>
Continuum measurements are conducted between 86·0-92·0 GHz.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>92·0-94·0 GHz</td>
<td>FIXED MOBILE RADIOASTRONOMY RADIOLOCATION Diazenylium line observations conducted between 92·0-95·0 GHz MoD (for the Radiolocation service)</td>
</tr>
<tr>
<td>94·0-94·1 GHz</td>
<td>EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION UK5 SPACE-RESEARCH (active) Radioastronomy</td>
</tr>
<tr>
<td>94·1-95·0 GHz</td>
<td>FIXED MOBILE RADIOASTRONOMY RADIOLOCATION Diazenylium line observations conducted between 92·0-95·0 GHz MoD (for the Radiolocation service)</td>
</tr>
<tr>
<td>95·0-100·0 GHz</td>
<td>FIXED MOBILE MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE RADIOASTRONOMY Radionavigation</td>
</tr>
<tr>
<td></td>
<td>Used for multiple line and continuum observations between 97·88-98·08 GHz</td>
</tr>
</tbody>
</table>

88
Radio Systems at 60GHz and Above

ANNEX 7: Draft ECC Document ECC/REC/(05)07

RADIO FREQUENCY CHANNEL ARRANGEMENTS FOR FIXED SERVICE SYSTEMS
OPERATING IN THE BANDS 71-76 GHz AND 81 - 86 GHz

Recommendation approved by the Working Group "Spectrum Engineering" (WGSE)

INTRODUCTION

The millimetre wave spectrum above 70 GHz is of increasing interest to service providers and systems designers because of the wide bandwidth available for carrying communications at this frequency range. These wide bandwidths are valuable in supporting applications such as extremely-high-speed data transmission. Because of the unique nature of the propagation in the millimetre bands and possibility to employ highly directional (pencil-sized) beams, multiple services and applications can be implemented without interference concerns, thus ensuring highly efficient re-use of the frequency band.

The use of the 71 - 76 GHz and/or 81 - 86 GHz bands provides an inviting opportunity to cope with the future market demands for increasingly high bandwidth access, in particular for Internet-based applications. Fixed radio links may be deployed much quicker and in certain cases are more cost efficient than the wired networks, and as such the millimetre waves provide sufficient bandwidth for terrestrial fixed links to compete or complement the fibre optic based access networks. The competing FSO (Free space optics) systems are also emerging as a possible solution that on short distances can support broadband capabilities (1-10 Gbit/s) with reasonable availability and reliability.

In the proposed scenario of using the 71 - 76 GHz and/or 81 - 86 GHz band for fixed services, it appears possible to implement very high capacity (up to 10 Gbit/s) links with some 1-2 km hop lengths (line-of-sight conditions); these systems would allow a rapid and effective deployment of broadband capacity in areas where fibre optic cables are not available or are not cost-effective.

The main features of operating fixed radio systems in this region of spectrum may be summed up as follows:

- Availability of wide bandwidths, allowing for the low cost of traffic in terms of bit/sec/Hertz/Euro;
- Possibility of multiple channel frequency re-use, thanks to the unique propagation conditions, highly directional pencil-sized beams; this will also enable implementation of multiple services and applications without interference concerns, obviating the need for coordination;
- Radio links are much easier to install comparing to alternative wire-bound solutions like fibre optical links;
- Ability to ensure high security because of low possibility of interference/capture of signals.

Use of the spectrum above 70 GHz is the only viable solution for fixed links to achieve the above objectives. The lower FS band at around 52 GHz (28/56 MHz channels) has similar propagation conditions but does not provide sufficient space for truly wide band links.

Therefore the bands 71 - 76 GHz and 81 - 86 GHz may be considered suitable for high speed data FS links.

It should be noted that the bands 71 - 76 GHz and 81 - 86 GHz are used in some countries by other services or applications than FS civil links. In particular the bands 71 - 74 GHz and 81 - 84 GHz have been identified as NATO Type 3 bands, i.e. for possible military use in NATO Europe. This should be taken into account by administrations wishing to use whole or parts of the frequency bands 71 - 76 GHz and/or 81 - 86 GHz for civil FS links.
Radio Systems at 60GHz and Above

"The European Conference of Postal and Telecommunications Administrations,

considering

a) that ITU Radio Regulations (RR) and the European Table of Frequency Allocations and Utilisations (CEPT/ERC Report 25) allocate the bands 71 - 76 GHz and 81 - 86 GHz on a primary basis to Fixed Service as well as other co-primary services;

b) that the European Table of Frequency Allocations and Utilisations in ERC Report 25 identifies the bands 71 - 74 GHz and 81 - 84 GHz as harmonised military bands for defence systems, but recognises that these bands can be shared between civil and military users according to national requirements and legislation (see ECA footnote EU27);

c) that ITU RR No. 5.340 prohibits all emissions, inter alia, in the band 86 - 92 GHz, and care should be taken to limit FS out-of-band emissions into that band;

d) that ITU RR No.5.149 applies to the frequency range 81- 86 GHz which urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference;

e) that the propagation characteristics of the 71 - 76 GHz and 81 - 86 GHz are ideally suited for use of short range FS links in high density networks;

f) that, as the propagation loss difference in the bands 71 - 76 GHz vs. 81 - 86 GHz is within the range of 1 dB for the hop lengths of up to 2 km, this also suggests the possibility of using these two bands together for FDD links with large duplex separation, if necessary;

g) that the FS uses envisaged in this band include various transmission digital systems with different modulation schemes, system gains and providing high data rate capacities;

h) that a large number of new FS systems could be deployed in the range of 71 - 76 GHz and 81 - 86 GHz, relieving congestion in the lower frequency bands;

i) that the 79 GHz frequency band (77 - 81 GHz) has been designated to the SRR equipment in accordance with ECC/DEC(04)03;

recommends

1) that administrations wishing to use whole or parts of the frequency bands 71 - 76 GHz and/or 81 - 86 GHz for civil FS links should consider the channel arrangements given in Annex 1 and Annex 2 respectively;
Radio Systems at 60GHz and Above

2) that administrations wishing to assign duplex channels, may use the bands 71 - 76 GHz and 81 - 86 GHz as paired bands, or as a separate single bands containing internal duplex separation, as illustrated in Annex 3;

3) that when extremely high bit rate system with high system gain is required, administrations may allow flexible aggregation of any number of 250 MHz channels, as illustrated in Annex 3;

4) that until the relevant ETSI technical specifications for FS in these frequency bands are developed, administrations may find examples of technical parameters for civil FS links in these bands in Annex 4.

Note:

Please check the Office web site (http://www.ero.dk) for the up to date position on the implementation of this and other ECC Decisions.
Annex 1

RADIO-FREQUENCY CHANNEL ARRANGEMENTS IN THE BAND 71 - 76 GHz

Let \( f_r \) be the reference frequency of 71000 MHz,
\( f_c \) be the centre frequency of a radio-frequency channel in the band 71 - 76 GHz,
\( n \) be the channel number,

then the centre frequencies of individual channels with 250 MHz separation are expressed by the following relationship:

\[
fn = fr + 250\cdot n \quad \text{MHz}
\]

where:
\( n = 1, 2, 3, ..., 19 \)

Note, that the specified channels may be used to form either TDD or FDD systems within the single band, or in combination with other band specified in this recommendation.

Calculated parameters according to ITU-R Rec. 746

<table>
<thead>
<tr>
<th>XS MHz</th>
<th>n</th>
<th>( f_r ) MHz</th>
<th>( fn ) MHz</th>
<th>Z1S MHz</th>
<th>Z2S MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>1,...,19</td>
<td>71250</td>
<td>75750</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

TABLE A1.1

XS Separation between centre frequencies of adjacent channels
Z1S Separation between the lower band edge and the centre frequency of the first channel
Z2S Separation between centre frequencies of the final channel and the upper band edge
Let $f_r$ be the reference frequency of 81000 MHz, $f_n$ be the centre frequency of a radio-frequency channel in the band 81 - 86 GHz, $n$ be the channel number, then the centre frequencies of individual channels with 250 MHz separation are expressed by the following relationship:

$$f_n = f_r + 250n \text{ MHz}$$

where:

$$n = 1, 2, 3, ..., 19$$

Note, that the specified channels may be used to form either TDD or FDD systems within the single band, or in combination with other band specified in this recommendation.

### a. Calculated parameters according to ITU-R Rec. 746

### b. TABLE A2.1

<table>
<thead>
<tr>
<th>XS</th>
<th>Separation between centre frequencies of adjacent channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1S</td>
<td>Separation between the lower band edge and the centre frequency of the first channel</td>
</tr>
<tr>
<td>Z2S</td>
<td>Separation between centre frequencies of the final channel and the upper band edge</td>
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</tbody>
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<thead>
<tr>
<th></th>
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<td></td>
<td>H</td>
<td>z</td>
<td>S</td>
<td></td>
<td>z</td>
</tr>
<tr>
<td>3. M</td>
<td></td>
<td></td>
<td>H</td>
<td>H</td>
<td>10. M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>z</td>
<td>z</td>
<td></td>
<td></td>
<td>z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Separation between the lower band edge and the centre frequency of the first channel</td>
</tr>
<tr>
<td>Z2S</td>
<td>Separation between centre frequencies of the final channel and the upper band edge</td>
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</tbody>
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</tr>
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</thead>
<tbody>
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<tr>
<td>Z2S</td>
<td>Separation between centre frequencies of the final channel and the upper band edge</td>
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</tbody>
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<th>Separation between centre frequencies of adjacent channels</th>
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</thead>
<tbody>
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</tr>
<tr>
<td>Z2S</td>
<td>Separation between centre frequencies of the final channel and the upper band edge</td>
</tr>
</tbody>
</table>
Annex 3

EXAMPLES OF PAIRING AND AGGREGATING CHANNELS
IN FREQUENCY BANDS 71 - 76 / 81 - 86 GHz

The principle of using the channels from within the bands 71 - 76 GHz and 81 - 86 GHz in a single duplex FDD arrangement is described in the Fig. A3.1.

Fig. A3.1. Combining the channels from 71 - 76 / 81 - 86 GHz bands into a single FDD arrangement with duplex separation of 10 GHz

The principle of duplex channels within a single band 71 - 76 GHz or 81 - 86 GHz with duplex separation of less than 5 GHz is shown in Fig. A3.2.

Fig. A3.2. Combining the channels from single 71 - 76 GHz or 81 - 86 GHz band into an FDD arrangement with duplex separation of less than 5 GHz

When the wider channels are needed, e.g. for very high bitrate and high system gain applications (e.g. employing FSK modulation), then a flexible number of consecutive 250 MHz channels may be aggregated into FDD channels, as illustrated in Fig. A3.3 for duplex separation of 10 GHz or in Fig. A3.4 for duplex separation of less than 5 GHz.
Figure A3.3: Example of aggregating multiple 250 MHz channels, possibly alongside with original 250 MHz wide channels

Figure A3.4: Example of aggregating multiple 250 MHz channels, possibly alongside with original 250 MHz wide channels within the single band 71 - 76 or 81 - 86 GHz
Annex 4

PRELIMINARY EXAMPLES OF FS TECHNICAL PARAMETERS CONSIDERED IN FREQUENCY BANDS 71 - 76 / 81 - 86 GHz

This annex provides examples of the key FS radio system parameters, which may be used by administrations as a guidance for interference evaluation and calculations for frequency sharing with other services in frequency bands 71 - 76 GHz and 81 - 86 GHz. These parameters should not be understood as regulatory limits.

The following tables set out the basic parameters for FS system, suited to transmit 1Gbit/s payload but exploiting different number of 250 MHz channels in 71 - 76 GHz frequency band and/or in 81 - 86 GHz frequency band, according to the arrangements given in Annexes 1-3 of this recommendation.

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>GHz</th>
<th>71 - 76</th>
<th>81 – 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Modulation scheme</td>
<td></td>
<td>128QAM</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Noise Figure @ Antenna Port</td>
<td>dB</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Receiver signal power for BER 10^-6</td>
<td>dBm</td>
<td>-56</td>
<td>-55</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Antenna radiation pattern</td>
<td></td>
<td>ITU-R F.699 and 1245</td>
<td></td>
</tr>
</tbody>
</table>

Table A4.1: Parameters for 1Gb/s FS link using one 250 MHz channel

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>GHz</th>
<th>71 - 76</th>
<th>81 – 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Modulation scheme</td>
<td></td>
<td>16QAM</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Noise Figure @ Antenna Port</td>
<td>dB</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Receiver signal power for BER 10^-6</td>
<td>dBm</td>
<td>-61</td>
<td>-60</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>7-14</td>
<td>6-14</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Antenna radiation pattern</td>
<td></td>
<td>ITU-R F.699 and 1245</td>
<td></td>
</tr>
</tbody>
</table>

Table A4.2: Parameters for 1Gb/s FS link using two aggregated 250 MHz channels

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>GHz</th>
<th>71 - 76</th>
<th>81 – 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>1250</td>
<td></td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Modulation scheme</td>
<td></td>
<td>FSK</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Noise Figure @ Antenna Port</td>
<td>dB</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Receiver signal power for BER 10^-6</td>
<td>dBm</td>
<td>-64</td>
<td>-63</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>14-20</td>
<td>14-20</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Antenna radiation pattern</td>
<td></td>
<td>ITU-R F.699 and 1245</td>
<td></td>
</tr>
</tbody>
</table>

Table A4.3: Parameters for 1Gb/s FS link using five aggregated 250 MHz channels
EXAMPLES OF FS EQUIPMENT TO BE USED IN FREQUENCY BANDS 71-76/81-86 GHz

This annex provides details of the key radio system parameters, required for interference evaluation and calculations for frequency sharing with other services in frequency bands 71-76 GHz and 81-86 GHz.

The following tables set out the basic parameters for FS system, suited to transmit 1Gbit/s payload but exploiting different number of 250 MHz channels in 71-76 GHz frequency band and/or in 81-86 GHz frequency band, according to the arrangements given in Annexes 1-3 of this recommendation.

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>71 - 76</th>
<th>81 - 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>250</td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>128QAM</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
<td>190</td>
</tr>
<tr>
<td>Noise Figure @ Antenna Port</td>
<td>dB</td>
<td>12</td>
</tr>
<tr>
<td>Receiver signal power for BER 10-6</td>
<td>dBm</td>
<td>-56</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>5</td>
</tr>
<tr>
<td>Estimated maximum output power density</td>
<td>dBm/MHz</td>
<td>-15</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
</tr>
<tr>
<td>Antenna radiation pattern</td>
<td>ITU-R F.699 and 1245</td>
<td></td>
</tr>
</tbody>
</table>

Table A4.1: Parameters for 1Gb/s FS link using one 250 MHz channel

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>71 - 76</th>
<th>81 - 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>500</td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>16QAM</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
<td>350</td>
</tr>
<tr>
<td>Noise Figure @ Antenna Port</td>
<td>dB</td>
<td>12</td>
</tr>
<tr>
<td>Receiver signal power for BER 10-6</td>
<td>dBm</td>
<td>-61</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>7</td>
</tr>
<tr>
<td>Estimated maximum output power density</td>
<td>dBm/MHz</td>
<td>-15</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
</tr>
<tr>
<td>Antenna radiation pattern</td>
<td>ITU-R F.699 and 1245</td>
<td></td>
</tr>
</tbody>
</table>

Table A4.2: Parameters for 1Gb/s FS link using two aggregated 250 MHz channels

<table>
<thead>
<tr>
<th>Frequency bands</th>
<th>71 - 76</th>
<th>81 - 86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth (MHz)</td>
<td>MHz</td>
<td>1250</td>
</tr>
<tr>
<td>Payload rate (Gbit/s)</td>
<td>Gbit/s</td>
<td>1</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>FSK</td>
<td></td>
</tr>
<tr>
<td>Receiver Noise bandwidth</td>
<td>MHz</td>
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</tr>
<tr>
<td>Receiver signal power for BER 10-6</td>
<td>dBm</td>
<td>-64</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>dB</td>
<td>50</td>
</tr>
<tr>
<td>Maximum output power level @ antenna port</td>
<td>dBm</td>
<td>14</td>
</tr>
<tr>
<td>Estimated maximum output power density</td>
<td>dBm/MHz</td>
<td>-16</td>
</tr>
<tr>
<td>Additional feeder losses</td>
<td>dB</td>
<td>0</td>
</tr>
<tr>
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<td>ITU-R F.699 and 1245</td>
<td></td>
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Table A4.3: Parameters for 1Gb/s FS link using five aggregated 250 MHz channels
ANNEX 8: ECC Document ECC/REC/(05)02

“USE OF THE 64-66 GHz FREQUENCY BAND FOR FIXED SERVICE”

Recommendation approved by the Working Group "Spectrum Engineering" (SE)

INTRODUCTION

The band 64-66 GHz has been opened for use by fixed service (FS) systems in some European countries. In particular, this band seems very suitable for very short distance links deployed in dense scenarios. This recommendation provides an approach for deployment of such FS links in this band.

It is considered that the physical propagation features in this band make possible a lighter licensing regime than usually used for FS systems, which may include access to spectrum through the use of flexible frequency arrangements, block (or blocks).

“The choice of the appropriate assignment method remains a decision for national administrations.

considering

a) that the 64-66 GHz band is allocated to the Fixed Service on a Primary Basis in the European Common Allocation table and the ITU Radio Regulations (RR);
b) that this band is also allocated to other radiocommunications services on a co-primary basis;
c) that ITU RR No. 5.547 identifies the 64-66 GHz band for high density applications in the FS;
d) that the 64-66 GHz band is suitable for the deployment of high capacity point-to-point links;
e) that ETSI has developed TS 102 329 for the FS point-to-point equipment in this frequency band;
f) that the very short distance links in the 64-66 GHz band call for a light licensing regime;
g) that the atmospheric attenuation in this band may not be sufficient to ensure that a high density of links can be achieved without suitable management to avoid interference;
h) that the information on fixed links to be deployed in this band will be required to evaluate the impact of new links on existing links;
i) that for those administrations wishing to examine in their national assignment process if the interference threshold has been exceeded, interference criteria need to be defined;
j) that the level of interference threshold of a victim receiver may be also established based on ECC/REC 01-05;
recommends

1. that the use of FS in the 64-66 GHz band be limited to point-to-point systems;

2. that operating frequencies for point-to-point links in this band be assigned or recorded on a link-by-link basis;

3. that for administrations or operators wishing to determine the impact of new links on existing links, single and aggregate interference criteria may be derived using guidance given in ECC/REC 01-05. An example of applying this procedure for FS in the band 64-66 GHz is given in Annex 1;

4. that administrations who wish to implement a light licensing regime for FS links in this frequency band may refer to the example provided in Annex 2;

5. that administrations choose either to allow assignments in this band without a specific channel arrangement, or establish an arrangement based on simplified frequency slots arrangement as shown in Annex 3;

6. that administrations who wish to use the block assignment procedure form blocks consistent with the frequency slots arrangement given in Annex 3, defining suitable safeguards for interference avoidance between adjacent blocks.”
Annex 1

EXAMPLE OF DERIVATION OF INTERFERENCE CRITERIA

The interference criteria for single entry and aggregate interference can be derived from the characteristics of the equipment. As an illustration, the following figures in Table A1.1 are taken from the Annex B (Informative) of ETSI TS 102 329.

<table>
<thead>
<tr>
<th>Bit-rate (Mbit/s)</th>
<th>Maximum Occupied bandwidth (MHz) (Note 1)</th>
<th>Nominal duplex separation (MHz)</th>
<th>RSL for BER ≤ 10⁻⁶ (dBm)</th>
<th>RSL for BER ≤ 10⁻⁸ (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>500</td>
<td>850</td>
<td>-61</td>
<td>-59.5</td>
</tr>
<tr>
<td>155</td>
<td>620</td>
<td>850</td>
<td>-60</td>
<td>-58.5</td>
</tr>
<tr>
<td>622</td>
<td>1250 (Note 2)</td>
<td></td>
<td>-48</td>
<td>-46.5</td>
</tr>
<tr>
<td>1250</td>
<td>2000 (Note 2)</td>
<td></td>
<td>-42</td>
<td>-40.5</td>
</tr>
</tbody>
</table>

Note 1: these values are relevant for the 99% power containment for the simplest spectral efficiency Class 1 (e.g. On-Off-Keying) equipment as defined within EN 302 217-2-1.

Note 2: the occupied bandwidth of 622 and 1250 Mbit/s systems may preclude duplex operation, and therefore do not have a duplex separation value.

Table A1.1: BER as a function of Receive Signal Level (RSL)

In addition the ETSI TS specifies that a co-channel interference with C/I=23 dB should result in RSL degradation of no more than 1 dB for the above stated BER ≤ 10⁻⁶ thresholds, and C/I=19 dB should result in RSL degradation of no more than 3 dB.

Assuming that this recommendation is relevant to flexible system bandwidth, the triggers for defining acceptable interference should be defined in terms of absolute interference power density determining an I/N = - 6 dB for 1 dB degradation (single entry interference) and I/N=−2 dB for 3 dB degradation (aggregate interference).

This can be derived, for example, from the data in Table A1.1 above with the simple assumption that the equivalent system noise bandwidth is ~ 30% less than the Occupied Bandwidth (e.g. a OccBw=500 MHz corresponds to an equivalent NoiseBw ~350 MHz).

The figure of C/I=−23 dB for 1dB degradation implies a 6 dB lower system C/N (C/N = 17dB). Therefore from the -61 dBm figure for the 500 MHz system, it is possible to derive the parameters necessary for defining the trigger interference power density level:

- Receiver Noise Density: N (dBm/MHz)= -61 – 17 – 10log(500*0.7)= - 103.5 dBm/MHz

Therefore in this example the interference criteria for single entry interference could be expressed as follows:

- Trigger Interference Power Density I (for 1 dB degradation) = -103.5 – 6 = -109.5 dBm/MHz.

Similarly, the interference criteria for aggregate interference in this example could be expressed as follows:

- Trigger Interference Power Density I (for 3 dB degradation)= -103.5 – 2 = -105.5 dBm/MHz

Note: the possible variation of the percentage ratio between noise bandwidth and the Occupied Bandwidth, due to different implementation (e.g. roll-off factor), is considered contained within an additional ±10%, resulting in an error of − ± 0.5 dB.
To assist the planning of links, a light licensing approach can be considered. The light licensing regime does not mean licence exempt use, but rather using a simplified set of conventional licensing mechanisms and attributes within the scope decided by administration. This planning is delegated to the licensee.

This process at least requires that the Administration records the following set of simple criteria for each licensed link and makes the data available publicly (perhaps via the internet):

- **Date of application** (In order to assign priority);
- **Transmit and receive centre frequencies**;
- **Equipment type, specifying relevant transmitter/receiver parameters**: It is up to the administration to define this set of required parameters for recording. (To assist in the identification of operational parameters, to conduct interference analyses, e.g. following methodology in Annex 1);
- **Link location (geographic coordinates, height/direction of antenna)**;
- **The antenna gain and radiation pattern envelope**: (e.g. derived from ETSI TS 102 329, which specifies two alternative envelopes, class 2 and class 3).

Subject to the set of conditions set by the administration, it is left to the operator to conduct any compatibility studies or coordinate as necessary to ensure that harmful interference is not caused to existing links registered in the database. For example, an operator wishing to install a new link could calculate the interference that the new link will create to the existing links in the database. Then it will be possible to determine whether this new link will interfere with existing links. If so, the new link could be re-planned to meet the interference requirements of existing links in the database. Otherwise, the new link may be also co-ordinated with existing operators, who might suffer from the interference.

To assist with the resolution of disputes, licences are issued with a “date of priority”: interference complaints between licensees may therefore be resolved on the basis of these dates of priority (as with international assignments).
Annex 3

EXAMPLES OF POSSIBLE FREQUENCY SLOT ARRANGEMENTS
IN THE BAND 64.0 – 66.0 GHz

This annex gives examples of frequency slot arrangements for both FDD and TDD applications. The 30 MHz slots for both types of applications can be aggregated to form larger blocks/channels as required by the national administration.

FDD arrangement

Figure A3.1 shows the basic FDD arrangement consisting of 33 paired 30 MHz slots, which can be aggregated to form paired FDD channels/blocks consisting of several slots.

<table>
<thead>
<tr>
<th>10 MHz</th>
<th>33x30 MHz slots</th>
<th>33x30 MHz slots</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>64000</td>
<td></td>
<td></td>
<td>65990</td>
</tr>
<tr>
<td>64010</td>
<td></td>
<td></td>
<td>66000</td>
</tr>
</tbody>
</table>

Figure A3.1: Frequency Division Duplex arrangement (duplex separation: 990 MHz)

TDD arrangement

Figure A3.2 shows the basic TDD arrangement consisting of 66 slots of 30 MHz, which can be aggregated to form TDD channels/blocks consisting of several slots.

<table>
<thead>
<tr>
<th>10 MHz</th>
<th>66x30 MHz slots</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>64000</td>
<td></td>
<td>65990</td>
</tr>
<tr>
<td>64010</td>
<td></td>
<td>66000</td>
</tr>
</tbody>
</table>

Figure A3.2: Time Division Duplex arrangement
ANNEX 9: Responses to Surveys - Regulators
European National Regulators

- **Austria**
  Herbert Waxenegger,
  Federal Ministry for Transport,
  Innovation and Technology,
  Ghegastrasse 1A-1030,
  Vienna,
  Austria.
  Phone: +43 1 797 31 42 11.
  Fax: +43 1 797 31 42 09
  herbert.waxenegger@bmvit.gv.at

  None of the above bands are open yet.
  No decision has been taken on the licensing approach should they be opened.
  Information will be posted on [http://www.bmvit.gv.at](http://www.bmvit.gv.at)

- **Cyprus**
  Anastasios Elia,
  Electronic Communications Officer,
  Department of Electronic Communications,
  Ministry of Communications and Works,
  P.O.Box: 24647,
  CY-1302 Nicosia,
  Republic of Cyprus.
  Tel: +357 22 814875/872,
  Fax:+357 22
  321925aelia@mcw.gov.cy

  No-one has applied, nor has authorisation been given, for 60-100GHz operation.
  The regulator will review the situation if/when applications are submitted.

- **Czech Republic**
  Petr Zeman, on behalf of Zdenek Voparil
  Director of International Relation Department
  Czech Republic.
  zemanp@ctu.cz

  64-66 GHz : lightly licensed
  74-76 GHz : lightly licensed
  84-86 GHz : lightly licensed
  92-100 GHz : not licensed

- **Denmark**

  None of the bands are open yet.
  If the 65GHz band opens, it is highly possible that a light licensing regime will be implemented.
Estonia
Signe Maurus
signe.maurus@sa.ee
Lada Jostina
Chief Specialist
Radio Frequency Management Dept
lada.jostina@sa.ee

All bands are open for fixed link use, and all are on a fully licensed basis. Further data is available on http://www.sa.ee

Finland
Kalle Pikkarainen
Radio Network Specialist, Radio Administration
Finnish Communications Regulatory Authority (FICORA)
tel +358 40 733 44 29
fax +358 9 69 66 410
kalle.pikkarainen@ficora.fi

All the bands are open for Fixed Link use, but there is no detailed channel plan. All are fully licensed. Finland follows the work of ECC PT SE19 actively. Further information is given in http://www.ficora.fi/englanti/radio/Taulukko5.htm

France
Mr satellite Deschamps,
ANFR – DPSAI,
78 avenue du Général de Gaulle,
BP400,
94 704 Maisons Alfort,
Cedex FRANCE.
Tel + 33 1 45 18 73 76
bdeschamps@compuserve.com

The situation is under review, with a policy to be formulated following SE19 decision. The information will be available on the EFIS web site. More information about civil use of FS is available from the ART web site: www.art-telecom.fr or from Mr. Dubreuil (didier.dubreuil@art-telecom.fr)

Germany
Meik Gawron
Regulatory Office for Posts and Telecommunications
Frequency Assignment for Fixed Wireless Systems
Assistant Head of Section - 226b
meik.gawron@regtp.de
Tel: +49-(0)-30-22480-370
None of the bands are yet open and there are no working or operator groups within the country that are active in these bands. Germany will follow presently emerging CEPT recommendations as far as possible. It is preferred that 59.3-66 GHz should be fully licensed. No decision on licensing rules has been taken for the other bands.

- 59.3-64 GHz: shared civil and military use
- 64-66 GHz: civil use only
- 71-75.5 GHz: shared civil and military use
- 75.5-76 GHz: civil use only
- 81-84 GHz: military use only
- 84-86 GHz: civil use only
- 92-95 GHz: shared civil and military use
- 95-100 GHz: military use only

**Hungary**
Emilia Petras
emilia.petras@ihm.gov.hu

None of the bands are open. Policy is set out in two decrees:
Minister Dec. No. 35/2004 (XII.28.)IHM

**Iceland**
Hordur Hardarson
Post and Telecom Administration
Tel: +354 510 1500
hrh@pta.is

All the bands are allocated according to ECC standards, but none of the bands are open yet. In fact there are no links above 26GHz in operation. All fixed links in Iceland require a licence today.

**Ireland**
Tara Kavanagh,
Comreg,
Ireland.
tara.kavanagh@comreg.ie

None of the bands are fully open; however, trial licences are now being issued.

**Liechtenstein**
Fari Hosseini,
Frequency Management
http://www.ak.llv.li/
Fari.Hosseini@ak.llv.li

‘Strategic’ bands are:
64-65 GHz fixed point-to-point links
71-76 GHz fixed point-to-point links; paired with 81-86 GHz
77-81 GHz UWB automotive SRR
81-86 GHz fixed point-to-point links; paired with 71-76 GHz
75.5-76 GHz is allocated to (and used by) amateurs until 2006

- **Lithuania**
  Mindaugas Zilinskas.
  mzilinskas@rrt.lt

All spectrum is open except 94.0-94.1 GHz.
All bands are lightly licensed.
The Plan for the Use of Radio Frequencies was approved 16 December 2003
Order Number 1V-167

- **Luxembourg**
  Roland Thurmes
  Institut Luxembourgeois de Régulation
  www.ilr.lu
  Tel: + 352 45884524
  Fax: + 352 45884588
  e-mail: roland.thurmes@ilr.lu

64-66 GHz is already open for fixed links.
59.3-64 GHz will be opened for fixed links at end-2005.
71-76 GHz is not open except for 71-74 GHz harmonised NATO band.
81-86 GHz is not open except for 81-84 GHz harmonised NATO band.
92-100 GHz is not open.
All open bands are fully licensed.
http://www.ilr.etat.lu/freq/legal/index.htm and
With the exception of the military allocations, there are no systems in operation.

- **Netherlands**
  Herman Teinsma,
  Ministerie van Economische Zaken,
  Agentschap Telecom,
  Frequentie Infrastructuren & Systemen,
  Postbus 450,
  9700 AL Groningen.
  T: +3150 –5877201,
  F: +3150-5877400,
  herman.teinsma@at-ez.nl

None of the bands are open. Further information on www.at-ez.nl/nfr/

- **Norway**
  Stein Gudbjorgsrud,
  Head of Planning and Polic/Frequency Department
stein.gudbjorgsrud@npt.no

64-66 GHz open. Currently drafting a text for the band 64-66 GHz. The band will either be licence-exempt or lightly licensed (in practice licence-exempt with possibility of registering base stations for protection). For the other bands the NPT has received no applications. A final decision on which part of the band to allocate for Fixed Links has therefore not been taken.

- **Poland**
  Alicja Gawlik,
  International Department,
  Office of Telecommunications and Post Regulation,
  URTiP,
  Poland
  A.Gawlik@urtip.gov.pl

  New contacts are dealing with the enquiry:
  Mr. Wikot Sega W.Sega@urtip.gov.pl - Director of Frequency Management Resources of URTiP and Mr. Stanislaw Wilkowski S.Wilkowski@urtip.gov.pl - Deputy Director of Frequency Management Resources.

- **Portugal**
  Luísa Mendes,
  Director,
  Spectrum Management Department.
  Tel. + 351 217212202
  Fax. + 351 217211006
  e-mail: luisa.mendes@anacom.pt

  None of the above bands open.

- **Sweden**
  Christian Sällström,
  National Post & Telecom Agency,
  Spectrum Management Department Fixed Radio and Satellite,
  Telephone +46 8 678 57 63,
  christian.sallstrom@pts.se

  No bands or part bands have been opened.

- **Slovenia**
  Marjan Trdin
  vodja sektorja za radiokomunikacije /head of radiocommunications sector
  Stegne 7, POB 418
  SI - 1000 Ljubljana,
  Slovenija
  Tel: + 386 (0)1 583 63 60
  Fax: +386 (0)1 511 11 01
  marjan.trdin@apek.si
64-66 GHz is open, lightly licensed. It is planned to open 74-76 GHz and 84-86 GHz, also on a lightly licensed basis. [www.apek.si](http://www.apek.si) gives information. However, the national entry on [www.efis.dk/search/general](http://www.efis.dk/search/general) is not up to date. T/R 22-03 is followed.

- **Switzerland**
  Ivan Franic,
  OFCOM Federal Office of Communications, Frequency Management,
  Zukunftstrasse 44,
  P.O. Box,
  CH-2501 Biel-Bienne,
  Phone +41 (0)32 327 55 11,
  Direct +41 (0)32 327 57 03,
  Fax +41 (0)32 327 56 66,
  [ivan.franic@bakom.admin.ch](mailto:ivan.franic@bakom.admin.ch)
  [http://www.bakom.ch](http://www.bakom.ch)

59.3-62 GHz, 64-66 GHz, 71-76 GHz, 81-86 GHz, 92-94 GHz, 94.1-100 GHz are open. All of these bands are Fully Licensed, due to sharing with military.
Non-European National Regulators

Sample data for non-European regulators is shown below. The information is based on returns to the questionnaires and on website data.

- **Taiwan**  
  Ching-Chich Lin (Mr.)  
  Director, Department of Radio Spectrum Management,  
  Directorate General of Telecommunications  

At the time of report preparation only an acknowledgement has been received. The enquiry has been referred to the relevant department; further information is promised.

- **Zambia**  
  Kephas Masiye  
  kmasiye@caz.gov.zm

All the bands in question are free at the moment. No operator has asked for spectrum in these bands.

- **Philippines**  
  Pricilla F. Demition  
  Chief, Frequency Management Division  
  fmd@ntc.gov.ph  

General frequency clearances and/or assignment is done by Frequency Management Division: fmd@ntc.gov.ph but licensing is done by various units:  
  1. Radio Regulations and Licensing Department for private networks, aeronautical services and maritime services: rrld@ntc.gov.ph  
  2. Common Carrier Authorization Department for common carrier services: ccad@ntc.gov.ph  
  3. Broadcast Services Department: bsd@ntc.gov.ph  

Follow up enquiries have been sent accordingly.

- **Japan**  
  Hideto Ikeda  
  ikeda637@oki.com

Band 59-66 GHz is available for unlicensed use, with the following specification:

- Maximum output power is 10 mW  
- Maximum antenna gain is 47 dBi  
- Frequency stability within +/-500 ppm  
- Maximum Bandwidth is 2.5 GHz

Radio Systems at 60 GHz and Above

- **Singapore**
  Ms Teo Geok Hoon  
  (65)6211 1903  
  teo_geok_hoon@ida.gov.sg

The 64-46 GHz bands have been made available by WRC-2000 for high-density applications in the fixed services (HDFS). The propagation condition and high degree of frequency reuse enable the use of frequency bands above 30GHz for high-density deployment of wireless point-to-point and point-to-multipoint systems. These bands are currently unoccupied and IDA will continue to monitor the developments in this area and the availability of equipment. In light of the high rainfall in Singapore, IDA welcomes any interested parties to conduct trial on HDFS systems in Singapore to investigate the feasibility of deploying such systems. IDA will make available these bands once there is a demand for use of these bands.

- **Israel**
  Mr. Meir Ben Basat  
  Tel. 03-5198231  
  benbassatm@moc.gov.il

The enquiry was forwarded to Mr. Basat, who is responsible for telecommunications services, including Bezeq services, international services and cellular telephony.

At the time of report preparation only an acknowledgement has been received.

- **Canada**

Policy is determined by Industry Canada.
http://www.ic.gc.ca/cmb/welcomeic.nsf/FICPages/ContactUs

This is also the government department responsible for the technical standards of telecommunication and radiocommunication equipment. Follow up enquiries have been sent accordingly.

Data below is taken from unpublished IEEE802.15-03 input paper (November 2005).

**Regulatory Documents**
(i) RSS-210, Issue 6, September 2005  
(ii) RSS-Gen, Issue 1, September 2005

Canadian and US regulatory requirements are harmonised.

**Operating frequency range**  
57.05 GHz to 64 GHz.

**Category I equipment, requiring certification from Industry Canada.**

**Output Power**

<table>
<thead>
<tr>
<th></th>
<th>≤ 9 μW/cm² at 3 m from the antenna aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power Density</td>
<td></td>
</tr>
<tr>
<td>Peak Power Density</td>
<td>≤ 18 μW/cm² at 3 m from the antenna aperture</td>
</tr>
</tbody>
</table>

Peak Transmitter Output Power  
<500 mW, in 100 MHz
Transmitters must have built-in identification such that within any one second interval of signal transmission, each transmitter with a peak output power equal to or greater than 0.1 mW or a peak power density equal to or greater than 3 nW/cm², as measured 3 meters from the radiating structure, must transmit a transmitter identification at least once. Each application for equipment authorisation for equipment that will be used inside a building must declare that the equipment contains the required transmitter identification feature and must specify a method whereby interested parties can obtain sufficient information, at no cost, to enable them to fully detect and decode this transmitter identification information. Upon the completion of decoding, the transmitter identification data block must provide the following fields:

- Industry Canada certification number, which shall be programmed at the factory.
- Manufacturer's serial number, which shall be programmed at the factory.
- Provision for at least 24 bytes of data relevant to the specific device, which shall be field programmable.

### USA – FCC

On February 8, 2005, the NTIA announced that the FCC will use an automated web-based licensing process in the 71-76GHz, 81-86 GHz and 92-95 GHz bands, the commission’s new communications Link Registration System (LRS). Filing can be completed through one of the three recently appointed FCC Database Managers that will utilize the new automated Web-based system set up by the National Telecommunications and Information Agency (NTIA) of the Department of Commerce.

A potential licensee simply has to log onto a secure website managed by any one of the three database managers. A simple form is completed with proposed end-point coordinates and frequency band information. The LRS manages all necessary filings and performs an interference analysis and path coordination, quickly returning a ‘green light’ indicating that the link is approved or an ‘orange light’ indicating that the coordination requires more extensive analysis. Ordinarily ‘green light’ approval can be achieved in less than 30 minutes. The cost of a license is around €100 for 10-years use.

The FCC proposed streamlined and simple licensing and interference protection rules that will allow business to take full advantage of multi-gigabit wireless technology. The FCC proposed to allow any individual or company to apply for license to operate 1 to 10 Gbps wireless systems; provide for point-to-point licenses as Part-101 Ruling extension which assure link integrity; provide for narrow beams (<1°) that allow for virtually unlimited links in any geographic area.

Past FCC Chairman Michael Powell hailed this licensing concept as revolutionary in increasing competition and reducing bureaucratic slowdown, and suggested a similar approach be adopted in all future US rulemakings.

A complete history of the 71-76 and 81-86 GHz filings can be found on the FCC’s Millimetre Wave 70-80-90 GHz Service website at [http://wireless.fcc.gov/services/millimeterwave](http://wireless.fcc.gov/services/millimeterwave)

Regulatory Document (i) CFR Title 47 Part 15.255
(ii) CFR Title 47 Part 15.209
Canadian and US regulatory requirements are harmonized. All other data as for Canada, above.

**Australia**

59.4 GHz to 62.9 GHz
Radiocommunications Class Licence 2000.
Output Power
(i) 10 mW (+10 dBm) maximum total peak transmitter power into the antenna
(ii) 150 W (+51.8 dBm) peak maximum EIRP

Above data taken from unpublished IEEE802.15-03 input paper (November 2005).
ANNEX 10: Responses to Surveys - Industry
**E Band Communications**
USA based. EBCC was incorporated at the end of 2003. EBCC designs and manufactures multi-gigabit capacity wireless communication systems based on 71-86GHz millimeter-wave radio technology. MMIC technology that enables EBCC to manufacture highest performance wireless systems with 1 to 10 Gbps throughput over the distances of several miles and availability up to 99.999%. EBCC’s “E-Link” system operates at E-Band spectrum at 71-76GHz, 81-86GHz, 92-95GHz. The market expects E-Band to solve last mile access bottleneck problem - connect enterprises to fibre networks, and enable backhaul of mobile (2.5G/3G) and fixed wireless (Wi-Fi, Wi-Max) networks. EBCC use’s Northrop Grumman Corporation for its E-Band Monolithic Microwave Integrated Circuit (MMIC) technology.

Products in the 71-76, 81-86GHz
Carrier-grade availability
Full Duplex data-rate from 1.25 Gbps to 10 Gbps
last mile with distance of 1 to 6 Miles
MMIC based technology Protocol independent

Contact:
Saul Umbrasas, Executive VP of Sales & Marketing

**GigaBit**
Gigabit Pt-Pt radios now available under $20k.

**GigaBeam**
Gigabeam was instrumental in opening up the 71-76 GHz and 81-86 GHz bands in the USA. Gigabeam’s founders provided the initial filing to the FCC to open up this spectrum, and also chair the Wireless Communications Association’s (an international wireless industry group) “Above 60 GHz Spectrum Development Committee” who championed the spectrum release and subsequent rule development through the FCC.

Gigabeam claim many deployments. An example is a metro area system for Manhattan, New York City, which will be built next year by GigaBeam as a fibre alternative, using the recently opened spectrum at 71-76GHz and 81-86GHz. It will use a tall building, at 32 Sixth Ave, as its main point of presence. See press releases on www.gigabeam.com. GigaBeam have also been awarded trial licences in Ireland.

The GigaBeam system can transmit at up to 3Gbps.

Doug Lockie, President,
GigaBeam Corporation
470 Springpark Place, Suite 900
Herndon, VA 20170, USA
+1 (571) 283 6200

jonathan.wells@gigabeam.com
www.gigabeam.com
**NewLans**
NewLans has submitted proposals to the IEEE for a future gigabit Wi-Fi standard, and is in the shorter term looking to develop proprietary gigabit technologies for 56GHz.

**Endwave**
Endwave is merchant supplier of RF sub-assemblies, and well-positioned to have overview of developing manufacturing market.

Whereas the 38GHz band has an installed base of over one million 'ends', the 60GHz band has probably only 10k ends. 'The market never matured - perhaps the present lobbying in the USA-FCC will help the cause.' In Europe, are seeing sales in 57,1-58,9 GHz band for micro-cellular BTS - costs are in range USD1000-1500 in current 'low' volume for E1. Market for GB/s links is very immature - probably only 100's in 2005 at USD10k per end.

70-80 GHz chipsets are at evaluation stage - around USD1k per end for the chipset. Price drivers are chipset, packaging, yield and investment recovery. Could lead to USD2-3k per end total. 'It is essential that lessons are learned from the roadmap of 38 GHz products.' Affordable radios will only be possible with MMIC's. Endwave are working on active and non-active hybrid MMIC's with 'flipped' chips.

Contact:
Mark Hebeisen, VP Marketing

**Huber - Suhner**
This Swiss group has a new developed wireless data link SENCITY®Link.

The product version SL60-100-57/64-E-O and will be available for the US market in compliance with FCC 15.255 part C. The product version SL60-100-57/64-E-O operates as a data link in the 60 GHz unlicensed band with a data rate of 100 Mbps over a distance of up to 1 km (3300 ft). operates on QPSK.

**Intel**
Intel are a merchant supplier of chips, MMIC's and RF sub-assemblies. They are working on CMOS MMIC's for up to 100 GHz.

Contact:
Luiz Franca-Neto

**Sprint**
Sprint are an operator. Sprint's customers 'demand ever-increasing bandwidth to implement new applications and converge voice and data networks.' He quoted Cisco as saying that 'fibre only connects 5% of the buildings that will need fibre-speeds; yet 75% of these are within one mile of a fibre POP, so could be connected at 60 GHz. Customers are placing increased stress on network redundancy, with other drivers being availability and speed to market.
Contact:
Randy Olsen, Product Manager.

**Progress Telecom**
Operator in south-east USA. Have 400k miles of fibre and about 200 POPs. Offering SONET/TDM based services, OC-12 connections. Voice, data and video. Believe the market needs a 12 month payback, with typical rates around USD7k per month. Users also want 'carrier grade' service, SNMP management or equivalent, and 99.999% availability with protection.

**Comsearch**
USA consultancy, designing and commissioning radio networks (not equipment). Have insights into FCC decisions at 71-95 GHz.

**Terabeam**
Radio manufacturer specialising in unlicensed bands. 'Gigalink' radios at 60 GHz and 73-83 GHz. Believe applications will include fibre extension, backhaul, and adding redundancy to existing dense networks. Say that 60GHz is maturing and affordable but 73-83 GHz kit will always be more expensive than 60 GHz because components are more difficult and because FCC rules require 1 bit/Hz min whereas 60 GHz has no limitations.

**Bridgewave**
60GHz links are approx 25% of cost of E-band links, have natural immunity to interference, but have shorter range. A killer application could be 'daisy-chaining' across power pylons to create a POP backbone for broadband ISPs.

GigE 60GHz product:
1000Base-SX
MAC layer transparent
1.25Gbps, full duplex
<50uS latency
~900m range at 99.999% availability (rain zone dependent)
Heavy FEC improves link margins and regenerates data for daisy-chained links.
USD19k per link to end-user (1-off), expected to be much less in high quantities.

BridgeWave Communications recently announced its new FE60 100 Mbps Ethernet wireless link. The list price for a FE60 link is $14,900.

Contact:
Gregg Levin, Senior VP Product Operations,
Santa Clara,
California.
www.bridgewave.com

**Loea Corporation**
Loea Corporation is a designer and manufacturer of ultra broadband fixed wireless telecommunication equipment operating in the upper millimeter wave spectrum from 71.0-86.0GHz. Loea claim to have been the first company to demonstrate a 71.0-
86.0GHz radio system (in 2001) ; first to deploy under Special Temporary Authority from the FCC (in 2002) ; to have been the key architect of the petition for Rule Making at the FCC in 2001 ; first to receive NTIA Equipment Certification (in 2003) ; first to achieve Equipment Certification from the FCC (2005).

L-2500 Transceiver features include:
High all weather availability with 99.999% at 1km in most place in the USA and a maximum reach of 5km.
Licensed spectrum with efficient licensing scheme to protect against interference and conserve time and cost.
Ultra high data rates, currently up to 1.25Gbps – full duplex (Gigabit Ethernet)
Plans for 2.5Gbps – full duplex (OC-48) and 10Gbps – full duplex (OC-192 or 10xGigE)
Built-in SNMP device monitoring capabilities and is plug-and-play with standard network equipment.

Loea’s Corporate headquarters are in San Jose, CA. Loea was incorporated in May 2001 and has had permanent systems deployed since 2002.

Rayawave
Rayawave has products at 60, 70, and 80 GHz currently in trials and available for purchase. Rayawave is headquartered in San Diego.

http://www.rayawave.com/

Uses "Convolutional Lossless Feeding" design enables a powerful system that can be deployed at distances up to 5 km and at availabilities of 99.999% or better.

The 70/80 GHz products are the latest in the Rayawave portfolio of high speed radio products. These products maximize the distance and availability customers need today.

Introduced in 2003, the 100 and 1250 systems quickly have become the best-selling Rayawave products for Enterprise connectivity for distances up to 1000 meters.

The Rayawave 60 GHz indoor products have been used in factories throughout the world for high speed flexible connectivity needs.
5  RADIO CHANNEL CHARACTERISATION

5.1  INTRODUCTION

The performance of a radio system is limited by the ability of the receiver to reconstruct the signal that was transmitted. Limitations to this reconstruction are having sufficient energy per bit of information \( \{ E(b)/N_0 \} \) and that the signal is not too dispersed in time.

The signal available at the receiver is due to energy arriving via both direct and scattered routes from the transmitter. Within a point-to-point configuration the direct and indirect paths are a function of clutter in the primary Fresnel zones of the antenna and due to scattering from antenna side lobes.

The effect of dispersion (frequency selective fading) across the radio channel becomes more significant as the channel becomes wider. To support Gigabit Ethernet via a radio channel using low order modulation requires channel bandwidths in the region of 1 GHz.

For a Gigabit Ethernet radio using 4QAM (QPSK) modulation, the channel data rate including overhead will be approximately 700 M symbols / second. Energy dispersed between / across symbols will provide self-interference causing the link to fail. This can be mitigated through the use of adaptive time delay equalisers. Practical equalisers are able to span approximately 10 symbols. Thus channel echoes with delays of up to approximately 13\( n \) sec can be accommodated.

Without equalisation, 4QAM operation with self-interference levels in the range of 10 dB to 15 dB below the primary signal can be supported with forward error correction. More spectrally efficient modulation schemes (for example 8PSK or 16QAM) require further reductions in self-interference to 15 dB to 25 dB below the primary signal.

The channel soundings used here are able to investigate the distribution of the echoes and to present this as a power-delay profile for the path.

To provoke multi-path behaviour for short paths moderate directivity antennae have been used. The antennae used here were conical horns with a nominal gain of 20 dBi. Typical links within the 60 GHz band are using antenna with typically 40 dBi. These therefore exhibit an angular directivity ten times greater in both elevation and azimuth. The delay profile for a 100 m path with 20 dBi antennae would therefore scale to a 1000 m path with 40 dBi antennae.

Whilst there are numerous techniques that can be used to measure the channel the use of an FMCW (frequency modulated continuous wave) signal has advantages in particular for wide channels. These advantages include the optimum use of the available transmit power and the high processing gain at the receiver.

5.2  DURHAM 60 GHz CHANNEL SOUNDER

Equipment to translate the operational frequency of the Durham channel sounder into the 60 GHz band has been designed, assembled and demonstrated to operate.
This is an FMCW channel sounder using a 1040 MHz sweep signal in the range 61 - 62 GHz. This signal is transmitted from one end of the channel and is correlated with an identical sweep at the receiver to provide an output that can be processed by the existing signal conditioning and data acquisition system.

The complete channel sounder system consists of a transmitter and a receiver that can be operated remotely from each other to support a complete link. There is no necessity to interconnect between the transmitter and the receiver since a Rubidium standard is used as a reference time base in both units.

The transmitter and receiver equipment is configurable (by changing programming parameters) to support frequencies in the range from 61 GHz to 67 GHz with the present hardware configuration.

The concept can be expanded to provide a channel sounder within the range 30 GHz to 110 GHz by replacing the mm-wave hardware elements only.

5.3 CHANNEL SOUNDER CALIBRATION AND VERIFICATION

The channel sounder has been evaluated using two approaches:

Fixed Frequency Evaluation

The performance limits of the 60G Hz up and down converter system has been evaluated using auxiliary low noise signal sources in place of the 2 GHz chirp signals that are provided by the core channel sounder.

The result of this portion of the evaluation demonstrates a spurious limit of > 30dB below the primary signal. The spurious signals that are present are due to low level feed-through of system clock and other periodic perturbations. These components are identifiable due to the symmetrical, fixed nature of the signals and could if required be factored from the data.

Data from the spectrum analyser is included within the description of the hardware in annex 2.

Frequency Chirp Evaluation

The fixed signal sources are replaced using the chirp waveforms. A configuration with low multi-path is used for this configuration. To achieve this a short, direct path between the transmit and receive antennae with no clutter was arranged.

The result of this test was that a sharp primary signal was observed with some additional spurious signals present at ~ -20 dB below the main signal. These spurious signals are due to spurious components from the wideband DDFS used in the base channel sounder that are then further degraded due to the additional X4 multiplication used by the frequency conversion process.
To confirm that multi-path behaviour could be usefully observed a deliberately multi-path rich configuration was contrived. In this configuration the transmit and receive antennae were each pointed vertically (away from one another) with propagation due to reflections from the laboratory ceiling structure.

A significant modulation could be observed on the time series data with identifiably separate path delays on the power - delay profile.

The time series, power delay profile and channel amplitude / frequency plots are included in within the channel soundings in Annex 1.

**5.4 RESULTS OF CHANNEL SOUNDINGS**

Refer to Annex 1 for channel sounding data and in-building locations.

(a) In-building

Line of sight (data sets 1 and 2)

For an LOS path within the corridor no significant additional multi-path components were observed. The measurement was repeated for a small change in the alignment of the equipment.

Two non line of sight configurations were explored.

For the first NLOS configuration (data set 3), the antenna were deliberately aligned orthogonally with the transmit antenna pointed to the ceiling. We observed many multi-path components with significant energy dispersal across ~ 25 nsec. The signal to noise ratio remained relatively high such that with equalisation or using delay tolerant forms of modulation a link should be viable.

In the second NLOS configuration (data set 4) the antennae were aligned in the horizontal plane. However the transmitter was moved around a corner and was operated through a pair of glazed doors. Here only one significant multi-path component was observed with a relative amplitude of -8 dBC at 10 nsec delay. More significantly however the signal to noise ratio was significantly reduced. It is probable therefore that a whilst the delay component could be successfully accommodated using equalisation techniques the link would not be viable due to limited signal to noise ratio.

Contrasting the channel transfer functions, in the first NLOS configuration the signal level is mostly high across the channel with reductions in level by ~ 10 to 15 dB occurring in places across the band. In the second approach however, the transmission is generally at a relatively lower level with a small number of discrete peaks where the transmission loss was sharply reduced.
(b) Operation from building to building.

In these configurations the transmitter and receiver were each operated within the building. However the path included transitions from inside to outside the building through conventional glazed windows.

For the first of these configurations (data set 5) the path was arranged to be approximately normal to the glazing (within 10 degrees). Operation was through two glazed units, one close to the transmitter and one close to the receiver. No significant multi-path components were observed. A reduction in transmission of ~ 10 dB was observed in the centre of the swept band at around 61.5 GHz.

In the second of these configurations (data set 6) the measurement was along a longer path at a grazing incidence to the glazing of approximately 45 degrees with a total of four glazing panels present in the path. A delay component at ~ 10 nsec can be observed with a relative amplitude of ~ -17 dBc. The attenuation that had previously been observed around 61.5 GHz was observed to shift further up the band.

(c) Building to building operation.

(For the purpose of this measurement the channel sounder receiver required access to 240V mains power as one of the batteries had been mechanically damaged.)

To provide building to building operation the channel sounder transmitter was powered from batteries and placed opposite the communications laboratory at a distance of ~ 100 m. This location included building clutter at about 1.5 m below the line of sight path. In addition the receiver was located relatively close (~ 6 m) to an included corner in the building. The receiver was operated inside the laboratory with the antenna pointed through an open window. This is data set (7).

Additionally a second set of data (set 8) was taken with the window closed. This was a double glazed unit with a set of horizontal Aluminium window blind slats. These were set in the “open” position.

In both cases discrete multi-path components at ~ -10 dBc at ~ 4 nsec and ~ 11 nsec are visible. These multi-path components are not explained by reflections directly from the flat roof in the centre of the path. However, they can be rationalised in terms of reflection from the adjacent building resulting in an off-axis path into the receiver. This would not be a significant factor had an antenna more appropriate to a real data link been utilised due to the higher angular discrimination.

5.5 Conclusions

1. Subject to the use of appropriate directional antennae line of sight paths operated with low levels of multi-path components both in building and out of building.

2. Operation through glass was demonstrated with little degradation in multi-path behaviour particularly for near normal incidence. Some smooth frequency selective behaviour was observable across the frequency band measured.
3. Non line of sight propagation was observed to result in a wide spread of delay components of near equal amplitude within a single corridor.

4. Non line of sight propagation around an obstacle was observed to occur at discrete frequencies across the measured band. At other frequencies transmission was attenuated.

5. For outdoor links the strong reflection from adjacent structures must be considered when selecting the antennae and the location of the terminal equipment.
Annex 1: Channel sounding measurements in the Durham School of Engineering.

A brief investigation of channel behaviour was made within the school of engineering at the University of Durham.

Plan of University of Durham School of Engineering.

The receiver was placed at the location marked (RX) on the plan. The transmitter was positioned at locations (1) through (6).

Position (1): Corridor, separation 20m, LOS.
Position (2): Repeat of (1) above with minor change of alignment.
Position (3): RX horn turned through 90 degrees (vertical alignment).
Position (4): Operating NLOS (transmitter taken around the corner).
Position (5): Indoor to outdoor to indoor signal normal to the glazing in windows.
Position (6): Indoor to outdoor to indoor signal with 45 degree incidence to the glazing.
Additionally a channel was established between the Communications Lab and a remote site outside the building. The spacing was ~ 100 m and included a flat roof ~ 1.5 m below the LOS path. Measurement (7) is a through the open window. Measurement (8) is through a closed window with a horizontal slat blind with the slats in the “open” position.
Fig. A1.1.1. Time series position 1

Fig. A1.1.2. Power delay position 1
Fig. A1.1.3. Channel transfer function for position 1

Fig. A1.2.1. Time series position 2
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Fig. A1.2.2. Power delay position 2

Fig. A1.2.3. Channel transfer function for position 2
Fig. A1.3.1. Time series position 3

Fig. A1.3.2. Power delay position 3
Fig. A1.3.3. Channel transfer function for position 3

Fig. A1.4.1. Time series position 4
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Fig. A1.4.2. Power delay position 4

Fig. A1.4.3. Channel transfer function for position 4
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Fig. A1.5.1. Time series position 5

Fig. A1.5.2. Power delay position 5
Fig. A1.5.3. Channel transfer function for position 5

Fig. A1.6.1. Time series position 6
Fig. A1.6.2. Power delay position 6

Fig. A1.6.3. Channel transfer function for position 6
Fig. A1.7.1. Time series position 7

Fig. A1.7.2. Power delay position 7
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Fig. A1.7.3. Channel transfer function for position 7

Fig. A1.8.1. Time series position 8
Fig. A1.8.2. Power delay position 8

Fig. A1.8.3. Channel transfer function for position 8
Annex 2: Description of the channel sounder transmit and receive hardware developed to support the project.

A2.1 Transmitter Description

Figure A2.1 documents the block diagram of the upgraded transmitter.

This block diagram is relevant both in terms of supporting the 60 GHz channel sounder and as a practical example of a mm-wave transmitter capable of operation in this frequency band.

Figure A2.1 RF section of the 60 GHz transmitter

The units that needed new design and construction are highlighted in grey. Units previously designed for other projects that needed to be built are indicated in yellow. The remaining items were purchased for the purposes of the project.

To capitalise on the functionality of the existing sounder, both the transmitter and the receiver use the existing channel sounder linear frequency chirps over the range 1.97 GHz to 2.23 GHz. The new unit comprises three main modules to convert the ~ 2 GHz chirp to 60 GHz. The first stage converts the output to a range between 5.00 GHz to 5.26 GHz using a previously designed 5.8 GHz up converter. The second stage translates the frequency sweep to 15 GHz, which is converted to 60 GHz using a quadruple multiplier. This results in both frequency translation and bandwidth enhancement.

To realise the three stages of up conversion the following units were designed and built. A new local oscillator module, which includes a multiplier circuit to convert the 10
MHz reference signal to 40 MHz was designed to phase lock a source operating at 2.56 GHz. This source is subsequently doubled to provide an output at 5.12 GHz.

The multiplication of the reference from 10 MHz to 40 MHz allows the synthesiser division ratio to be reduced to 40. This reduces the closed loop noise floor by approximately 7 dB. The reduction in division by four provides a 12 dB enhancement, however 5 dB is then lost due to the degraded performance of the phase-frequency divider at the higher comparison frequency. One disadvantage of this approach is that contiguous 40 MHz steps cannot be achieved. The synthesiser can now support 2560 MHz to 2720 MHz in 40 MHz steps. This module includes a doubler to provide an output at 5.12 GHz.

The second up converter stage has a frequency doubler for the local oscillator module output to generate a fixed 10.24 GHz local oscillator. This is subsequently mixed with the sweep in the range 5.00 GHz to 5.26 GHz to up-convert the chirp to the range 15.24 GHz to 15.50 GHz. This signal is filtered and amplified to provide an input level of +12 dBm to the final multiplier.

The third stage has a multiplier which is contained in a small aluminium enclosure with a waveguide interface to provide direct connection to the antenna. A 2m long flexible cable connects to the up-converter. With an input of 15.24 GHz to 15.50 GHz the module provides an output of nominally 5 mW (+7 dBm) at 60.96 GHz to 62.00 GHz.

The first three modules above (5 GHz up-converter, 5.12 GHz local oscillator and 15 GHz up-converter) are contained in a 3U 19 inch rack along with the power supply / micro-controller module.
A2.2 Receiver Description

The block diagram of the receiver is shown in figure A2.2.

This block diagram is relevant both in terms of supporting the 60 GHz channel sounder and as a practical example of a mm-wave receiver capable of operation in this frequency band.

![Sounder Receive Converter For 61GHz To 67GHz](image)

**Figure A2.2**: RF section of the 60 GHz receiver.

The receiver consists of up-converter modules similar to those at the transmitter to generate a frequency sweep at 61 GHz which is then used to mix with the received signal. To acquire the data with the existing data acquisition unit (which operates optimally within the frequency range 30 kHz to 300 kHz) the various units indicated in grey in the second stage of the receiver were designed and built.

The output from the mixer is the beat signal derived from the swept signal received from the transmitter and the local swept signal at the receiver. These two signals are sweeping over identical frequency ranges at the same rate. By off-setting the start point between the two sweeps an arbitrary beat signal can be derived. In the present configuration the difference frequency is nominally 12.53 MHz to 12.8 MHz. This signal is amplified using a two stage amplifier that includes a 5 bit switched attenuator to provide gain adjustment over a 31 dB range. The design has a measured noise figure of 3 dB and a 1 dB compression point of +12 dBm. Since the design uses feedback the distortion is very low up to the level at which output clipping occurs.
The output of the amplifier is then down-converted to provide a beat signal in the range 30 kHz to 300 kHz. This signal is then processed by the existing sounder signal conditioning and data acquisition units.

The down-converter includes a band-pass filter at 12.5 MHz to provide discrimination of the image frequency at 7.5 MHz due to down conversion to ~2.5 MHz (2.53 MHz to 2.8 MHz) using a 10 MHz local signal. The signals at 2.53 MHz to 2.8 MHz are then converted to base-band (30 kHz to 300 kHz) using a local signal at 2.5 MHz.

Since it is impractical to suppress the image frequency using filter techniques, a single-sideband conversion has been implemented. This requires a local oscillator signal that provides signals that are precisely in quadrature plus a broad band 90 degree phase shift network operating over the base-band frequency range.

The signal to be down-converted is provided to two down-conversion mixers each operated from the local oscillator with 90 degree difference between the two channels.

The quadrature local oscillator signals are derived using a four phase divider with a 10 MHz input to provide outputs at 2.5 MHz. This is implemented in fast CMOS logic. The phase difference was measured to be less than 0.1 degree from 90 degrees.

The outputs from these two mixers are then processed using a cascade of all-pass delay networks to provide a further differential phase shift of 90 degrees across the required base-band range (30 kHz to 300 kHz). A four plus four section design with a design ripple of 0.0075 degree has been implemented. Using 1% tolerance capacitors and 0.1% tolerance resistors an unwanted sideband rejection of 50 dB has been demonstrated [see figure A2.3].

The appropriate sideband can be selected by either adding or subtracting the two signals from the outputs of the broadband phase shift networks. (Subtraction is used in this case to select the upper sideband). The wanted sideband is reinforced and the unwanted sideband is cancelled.
A2.3 Converter Evaluation

It is necessary to characterise the equipment to confirm that it is capable of performing the measurements for which it has been designed.

To characterise the system a pair of low phase noise test sources have been designed and assembled to allow an end-to-end noise measurement of the system.

The measurements that have been performed provide confidence that the system is capable of observing delay components down to a relative level of ~ −20 dBc. This is sufficient to confirm that low order modulation (BPSK, 2-FSK, 3-FSK, 4-QAM and 8-PSK) could be supported by the channel with no equalisation.

Note. The 60 GHz converter modules provide a measurement limit of > 30 dBc. However, due to the multiplication (X4) of the basic sweep signal from the DDFS the spurious outputs from this source are degraded by 12 dB. This is responsible for the uncorrected measurement limit of the channel sounder. Since these distortion products occur at a fixed point in the delay spectrum they could if required be identified and factored from the results.
The delay spectrum (of figures A2.4 to A2.7) demonstrates a spurious limit of > 30 dB for the 60 GHz conversion process. The discrete tones are due to system clock and other repetitive interference sources within the frequency conversion system. (Systemic interference of this type produces spurious components that are symmetric around the primary signal).

Figure A2.4: Converter CW response 500 kHz span

Figure A2.5: Converter CW response 50 kHz span
At the transmitter a low-phase noise synthesised signal source at 2.000 GHz was used in place of the swept (2 GHz) signal. At the receiver a low-noise synthesised signal source at 2.003333 GHz was used in place of the swept signal. This provided a beat note of 13.333 MHz at the output of the 60 GHz mixer. This was down converted to 250 kHz using the single sideband down-converter.
The effective noise bandwidth of the signal processing is 250 Hz (the FFT bin size). The measured data demonstrates a general noise level of ~ -45 dBC within a 300 Hz bandwidth (closest spectrum analyser bandwidth) with discrete spurious signals at a level of -30 dBC. These discrete spurious signals are due to low level contamination of the power supplies due to power supply switching noise and system reference clocks.

### A2.4 Initial channel sounder measurement

An initial test was performed by setting up the transmitter and receiver to sweep over a 1040 MHz bandwidth with a 250 Hz waveform repetition frequency. This provides a sweep rate of 2.6*10E11 Hz/second. The units were separated by approximately 240 cm with 20 dBi gain conical horn antennas.

#### A2.4.1 Investigation of ideal “good” channel behaviour

For the first measurement the antennas were aligned to provide minimum levels of multi-path propagation. Figure A2.8 displays the acquired data for a single sweep.

![Sounder time-series data](image1)

**Figure A2.8:** Sounder time-series data.

The limited low frequency envelope modulation to the beat frequency indicates the lack of significant multi-path components.

![Power Delay Profile](image2)

**Figure A2.9.** 61 GHz delay profile (Fourier transform of the time series data).
A2.4.2 Investigation of ideal “multi-path rich” channel.

To contrast the “ideal good” channel behaviour the system was reconfigured to provide a high level of multi-path behaviour. This arrangement had both the transmit and receive sources separated by ~ 240 cm with each pointing vertically to the ceiling ~ 200 cm above the antennae.

The heavy envelope modulation is indicative of significant frequency selective behaviour due to multi-path propagation.
From these two sets of measurements we can conclude that multi-path propagation is observed by the channel sounder.

**Sounder Resolution**

A sample rate of 1Msample / second provides 4096 samples per sweep (4000 expanded to 4096). Each “bin” for the processed data output from the Fourier transform process is therefore:

\[ \frac{1 \text{E}6}{4096} = 244 \text{ Hz wide}. \]

The sweep rate is 250 sweeps / second * 1040E6 Hz / sweep = 2.6E11 Hz / second

Thus the ideal range resolution is:

\[ \frac{244 \text{Hz}}{2.6E11 \text{ Hz / second}} = 938 \text{ psec}. \]

The effect of the Hamming windowing of the data reduces this to ~1.2 nsec in practice.
A2.5 Hardware Photographs

Figure A2.14. 60 GHz RX front end.

The 60 GHz multiplier and mixer are located in the centre of the box lid.

The base-band amplifier is the lower printed circuit board. The single sideband down-converter is the upper printed circuit board.

Figure A2.15: 60 GHz TX front end.

Connections on the left are for power and RF stimulus at ¼ of the output frequency. The multiplier is attached to the centre of the lid of the box to provide a heat-sink. Subsequently an additional heat-sink was provided on the rear of the enclosure to improve power dissipation and to reduce the operating temperature.
Figure A2.16: Horn antenna (20 dBi on left, 10 dBi on right).

Figure A2.17: Transmit driver

Original modules are the power supply / controller (left half) and the 5.8 GHz up-converter (extreme right).

New modules are 2nd up-converter (with cables) and 2nd local oscillator next unit right.
Figure A2.18: Receiver driver (internal)

2 GHz to 5.8 GHz up-converter is on front panel. 2\textsuperscript{nd} local oscillator is on rear panel. 10 MHz to 40 MHz multiplier and -12V PSU are on the right panel (as viewed). Other microwave components are on the left panel.

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6 THE SPECTRUM EFFICIENCY OF FREQUENCY/POWER CONTROL

There is currently increasing pressure to make more efficient use of the radio spectrum, and to open up frequency bands where it is possible to provide the large bandwidths required for the next generations of radio systems such as mobile internet. The 60 GHz band is currently under-utilised, mainly due to the difficulties associated with compensating for the affects of rain attenuation experienced by frequencies in that range.

Adaptive Transmit Power Control (ATPC) has been proposed in the literature as a promising technique for opening up higher frequencies to commercial exploitation. It can also be used at lower frequencies to reduce the transmit power used during clear sky conditions and compensating for fading on a dB by dB basis. This would enable an increase in the rate of frequency re-use, and hence an improved spectral efficiency.

Radio systems operating at 60GHz and above are not currently efficient or economical due to the large fade margins required to compensate for the intermittent yet dramatic effects of rain fading. ATPC and Dynamic Frequency Diversity (DFD), are fade mitigation techniques which can help to make systems at these frequencies more economical, and hence more open to commercial exploitation.

6.1 ATPC (Adaptive Transmit Power Control)

6.1.1 ATPC operation

The basic principle for ATPC is quite simple. In cases where rain fading occurs on the radio path, it involves increasing the transmit power in order to be able to compensate for the fade. Given a reliable power control system, it is possible to reduce the fixed fade margin during clear sky conditions (i.e. no fading), thereby improving the rate of frequency reuse and link packing density in the geographical area of the link. This is because lower fade margins use less transmit power, which lessens the interference on adjacent links.

ATPC attempts to maintain the carrier to noise ratio (CNR) at the receiver of the terrestrial P-P link at the required level to achieve the desired quality of service (QoS) or bit error rate (BER), as appropriate. The CNR should always be greater or equal to the minimum CNR value calculated from detailed link power budgets. The basic operation of ATPC is illustrated in figure 6.1 [1].
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Let us assume that the system has been designed to achieve an unfaded CNR that is $\varepsilon$ dB greater than the minimum CNR. Whenever the CNR drops below the minimum CNR (green line in figure 6.1(a)), the link will be in outage if no action is taken. Hence ATPC is required to compensate for the link attenuation so that the QoS can be maintained as shown in figure 6.2(b). The transmit power is boosted on a dB per dB basis so as to compensate for the impact of the fade. This has the effect of keeping the CNR at its minimum value (see regions R1 and R3 in figure 6.1).

In practice, however, the dynamic range of the ATPC system will be limited to $R$ dB. This limitation implies that whenever the attenuation exceeds $\varepsilon + R$ dB with respect to the unfaded level, the fades will not be compensated. The resulting CNR, shown in area R2 of figure 6.1 (c), will drop below its minimum acceptable value and the system will be in outage.

In comparison with a non-ATPC system, the margin $\varepsilon + R$ dB corresponds with the rain fade margin as defined in Ofcom’s frequency assignment methodology, and as is shown in figure 6.2.

Figure 6.1: Principle of ATPC
6.1.2 Previous studies

The final report of an Ofcom study titled “Study to assess the impact of fade mitigation techniques in bands above 20 GHz” [1] indicated that there are spectrum gains to made as a result of introduction of ATPC in P-P fixed service bands, especially those operating at frequencies where rain is a significant attenuator. However, this study was limited in scope, dealing only with a simplified scenario of two parallel links in the 18 GHz band, separated by distances of ~ 1-10km.

Richardson et al, [2004] conclude that, for their scenario of two parallel links of length 5km, separated by distances of ~5km:

- ATPC allows a link to operate with a lower Tx power under clear sky conditions.
- Rain fading is highly correlated over the scenario area (~ 20-100 km²) for the 18 GHz band. Therefore, during rain events all paths are likely to fade, indicating that interference levels from an ATPC enabled link will stay at approximately the same level at the victim receiver even when the ATPC link is transmitting at full power.
- For the ATPC-only scenario the separation distance can be reduced with the amount of reduction being dependant on the choice of the Tx power margin.
- For mixed scenarios the separation distance can be similarly reduced without adversely affecting the performance of the non-ATPC link. However, the ATPC link will suffer a corresponding increase in interference power at its receiver and this must be compensated for when deploying the link by, for example, increasing the interference margin.
- For the area covered by the scenario, theoretical and simulation results considering the space-time properties of rain attenuation indicate that worst-case interference generated by an ATPC link is obtained during clear-sky conditions.
- Received signal level (RSL) is the preferred fade detection mechanism as it is only affected by rain fading. BER-led ATPC would result in an increase in Tx power as a response to increased interference, which could lead to a “domino
effect” where all links end up transmitting at their highest power, negating any spectrum gains.

- Management of ATPC links can be implemented in a distributed manner where each link operates independently.
- Benefits will arise to both individual operators (operational cost savings) and the industry as a whole due to the potential for reduced co-ordination distances and gains in spectrum utilisation.

Ofcom is currently funding a project entitled “Impact of introducing Automatic Transmit Power Control in P-P Fixed Service systems operating in bands above 13 GHz”. The outputs of the project are software tools to re-plan existing frequency plans, subject to a number of assumptions on the mix of ATPC and non-ATPC links and the type of ATPC in use, and evaluating the system performance by direct comparison between all-ATPC plans, non-ATPC plans and mixed plans. The project investigates in greater detail the impact of implementing ATPC in the 38 GHz band, using as a base the entire link planning database in that band. The final report of the project will give the results and conclusions in greater detail.

This report will expand on the work done in the previous two studies to take into account the impact of implementing ATPC in bands above 60 GHz.

6.2 DFD (Dynamic Frequency Diversity)

6.2.1 DFD operation

Dynamic Frequency Diversity (DFD) should not to be confused with DFS (dynamic frequency selection).

DFD involves using two co-located links, one at millimetre wave frequency and the other as a free space optical (FSO) link. The FSO link is not affected by rain, but is badly attenuated by fog, while the millimetre wave link is badly attenuated by rain, but not affected by fog. Switching between the millimetre wave link and the FSO link allows greater availability to be achieved than using one alone. Dual systems such as these potentially allow practical and economic operation of radio systems at millimetre wave frequencies.

DFS operates by dynamically switching between radio channels in a single band.

6.3 RAIN FIELD CORRELATION

Rain is the dominant attenuator at radio frequencies above ~10 GHz. ATPC is designed to compensate for rain fading. DFD can be implemented to compensate for the attenuating effects of fog or rain, depending on the operator’s choice of which link is to be the primary and which the secondary.

The best case scenario for ATPC is that the rain fading is completely correlated across the entire area of interest; i.e. the wanted and the unwanted links will be equally badly
affected by the rain field. If this is the case, then the problem then reduces to clear sky case.

The worst case scenario for ATPC is if the rain fading is completely uncorrelated across the entire area of interest; i.e. rain rate is at a maximum on the wanted link, while the unwanted link is not attenuated at all.

Millimetre wave communications applications typically need to operate over short paths (<10km), though interference paths may be longer. Hence there is a need to investigate the spatial autocorrelation function of rain and determine at what distances rain fields can be considered to be correlated or de-correlated.

6.3.1 Spatial and temporal analysis of meteorological radar data: Data description

The rainfall rate contours analysed in this research have been obtained by means of the Chilbolton Advanced Meteorological Radar (CAMRa), which is located in Hampshire in the south of England, at the latitude 51° 9' North and the longitude 1° 26' West. The climate is temperate maritime, with an average annual rain rate exceeded 0.01% of the time of approximately 22.5 mm/hr. The radar is a 25 m steerable antenna, equipped with a 3GHz Doppler-Polarization radar, and has an operational range of 100 km, and a beam width of 0.25°. To avoid reflections from ground clutter, maps of the rain rate field near the ground were produced by scanning with an inclination of 1.2°. These maps are produced on a polar grid, with a range resolution of 300m and an angular resolution of 0.3°. The number of maps produced in a given time period is dependent on the total angle scanned. The radar has a maximum angular velocity of 1°/second.

The radar scans were interpolated onto a square Cartesian grid, with a grid spacing of 300m and a side length of 56.4 km. Each grid contains 35344 data points (188²) covering more than 3100 km². The grids are separated in time by approximately 2 minutes.

6.3.2 Spatial autocorrelation of measured rain fields

Measurements [2] have shown that it can be assumed that the spatial correlation of rain falls off exponentially with distance for the first 50 km or so [see also 1]. The de-correlation for rain rate for large distances (up to 1000 km) and multiple stations was presented by Barbalisica et al., [3], using a very large rain gauge database covering the entire Italian territory. They have shown that for distances greater than 50 km the fall-off of spatial correlation with distance slows, though there can be jumps due to a recoupling effect resulting from the presence of another separate rainy event occurring at far distances at the same time. For their data, it was reported that statistical independence was reached for distances between sites greater than 800 km. However, for systems operating at 60 GHz and above, we can consider the spatial correlation of rain fields to fall off exponentially with distance, without being too concerned about the limits where this assumption breaks down.

Rain events can be subdivided into types according to the characteristic behaviour of the rain fields. Stratiform events tend to occur in the winter and spring months, and are
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events where it rains at low intensity for long periods (several hours). Stratiform events
tend to be very widespread, and in terms of meteorological radar measurements are
characterised by the presence of a bright band in the vertical scans. (The bright band
occurs at the melting layer, the height above the ground where the temperature is such
that liquid water and ice coexist. Below the melting layer, all the atmospheric water is in
the form of rain drops.) Convective events tend to occur in the summer and early
autumn months. They are characterised by their turbulent nature (i.e. there is no bright
band in the vertical radar scans). Convective events are short-lived and intense rain
events, which are also geographically localised, covering areas of only tens of km².
Frontal events are rare and are generally mixtures of stratiform and convective events.
For example, in the frontal event investigated here, a band of stratiform rain with
convective rain cells embedded in it was pushed across the country by a strong wind.

Figures 6.3a, 6.3b and 6.3c show the two-dimensional spatial autocorrelation function
calculated for three different types of event measured by CAMRa, convective, frontal
and stratiform respectively. As can be seen, the correlation coefficient falls off quickly
with distance in all three cases, approaching zero for distances of around 180 pixels
(corresponding to 54 km). This agrees well with the general assumption mentioned
above.

A key point is the differences in behaviour of the autocorrelation function for the
different event types. As can be seen, the autocorrelation function for the convective
event falls off more quickly with distance than the autocorrelation function for the
stratiform event. The autocorrelation function for the frontal event appears as a mixture
between the two others. This is due to the phenomenological behaviour of the different
types of rain event.
Figure 6.3a: Spatial autocorrelation for a convective event

Figure 6.3b: Spatial autocorrelation for a frontal event
**Figure 6.3c:** Spatial autocorrelation for a stratiform event

A better view of the fall-off of spatial correlation with distance can be seen in figures 6.4a, 6.4b and 6.4c. In these figures, radial cross-sections have been taken from the centre points of the auto-correlation plots at different angles to the edges.

**Figure 6.4a:** Radial sections through the spatial autocorrelation for a convective event
Figure 6.4b: Radial sections through the spatial autocorrelation for a frontal event
These figures show that the fall-off of autocorrelation coefficient with distance can be approximated by an exponential decay, as described in the literature, though as shown before, the rate of that decay is steeper in the convective rain fields than in the stratiform and frontal fields.

For distances of 0 to 40 pixels (0 to 12 km) the correlation factor varies from 1 to \(\sim 0.7\). As millimetre wave applications need to operate over short paths (<10km), we can effectively consider the rain field to be correlated over that distance. However, the rain isn’t completely correlated over those distances, hence we introduce an exponential rain model to give an indication of a more realistic worst case scenario given the presence of rain.

### 6.3.3 Exponential rain model

The worst case situation, that the rain field is completely decorrelated, doesn’t happen over the size of areas of interest for frequencies above 60 GHz. Hence a more realistic worst case rain scenario is needed.

We assume that the maximum rain rate is occurring on the wanted link, centred on the receiver, and that the rain rate falls exponentially with distance away from this point. Strictly speaking, it’s the correlation coefficient that falls exponentially with distance, but having the rain rate falling in line with the correlation coefficient gives us a more realistic worst case scenario.

The formula used was \( R(x) = R_0 e^{-\lambda x} \) where \( R(x) \) is the rain rate as a function of the distance from the centre point of the rain cell, \( R_0 \) is the rain rate value at the centre of the rain cell and was set to 25 mm/hr. The decay constant \( \lambda \) was 1/25.
Figure 6.5 shows the rain attenuation using the exponential rain model on an unwanted link for a range of frequencies and different link lengths. As the unwanted link length increases, the rain rate per kilometre decreases, hence the curve.

![Figure 6.5: Rain attenuation from the exponential rain model as a function of link length and frequency.](image)

### 6.4 LINK TOPOLOGIES

The link budget for a link is given by:

\[
P_R = P_T - A_T - A_R + G_T + G_R - 92.4 - 20 \cdot \log_{10} (d_{\text{tan}}) - 20 \cdot \log_{10} (f_{\text{GHz}}) - A_a - A_r^{0.01}
\]

where:
- \(P_R\) = Received Power (dBm)
- \(P_T\) = Transmitted Power (dBm)
- \(A_T, A_R\) = Tx / Rx Feeder Losses (dB)
- \(G_T, G_R\) = Tx / Rx Antenna Gain (dBi)
- \(d_{\text{tan}}\) = Link Length (km)
- \(f_{\text{GHz}}\) = Link Frequency (GHz)
- \(A_a\) = Atmospheric Attenuation (dB)
- \(A_r^{0.01}\) = Attenuation due to rain (dB)

Figure 6.6 shows the antenna gain as a function of angle, for a frequency of 60GHz. As can be seen, the antenna gain is at a peak when the transmitter and receiver are aligned (i.e. at an angle of 0 degrees). The antenna gain falls off rapidly with increased deviation from the correct alignment.
The scenario used in this study is shown in figure 6.7. It consists of two links operating at the same frequency and transmit power. The wanted link has a fixed length of 0.5 km and the transmit and receive angle of the unwanted link and the length of the unwanted link are variable.

The wanted to unwanted signal ratio is commonly used in the TFAC (Technical Frequency Assignment Criteria) to determine whether or not a proposed new link can be
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assigned. For the scenarios investigated in this report, where we are looking at two links operating with the same transmit and receive hardware, and transmitting at the same power levels and frequency, the W/U is given as follows:

\[
W/U = A_{\text{unwanted}} - A_{\text{wanted}} + 2G(0) - G(\theta) - G(\chi) - A_{\text{cls, wanted}} + A_{\text{cls, unwanted}} - A_{\text{rain, wanted}} + A_{\text{rain, unwanted}}
\]

where

- \(A_{\text{unwanted}}\) = Attenuation on the unwanted link due to Tx and Rx feeder losses (dB)
- \(A_{\text{wanted}}\) = Attenuation on the wanted link due to Tx and Rx feeder losses (dB)
- \(G()\) = Antenna gain as a function of incidence angle (dBi)
- \(A_{\text{cls, unwanted}}\) = Attenuation on the unwanted link due to clear sky attenuation (dB)
- \(A_{\text{cls, wanted}}\) = Attenuation on the wanted link due to clear sky attenuation (dB)
- \(A_{\text{rain, unwanted}}\) = Attenuation on the unwanted link due to rain attenuation (dB)
- \(A_{\text{rain, wanted}}\) = Attenuation on the wanted link due to rain attenuation (dB)

Figure 6.8 shows the W/U level as a function of the frequency of the links and the length of the unwanted link in clear sky conditions for the worst case scenario of the unwanted link being co-linear with the wanted link. As can be seen, as the unwanted link length increases, there is a gradual increase of W/U. In terms of frequency, this increase is more dramatic in the band around 60 GHz, but is a similar rate of increase at 100 GHz as at 50 GHz. Figure 6.9 shows the same graph, but in close up for distances of 0 to 10km.

![Figure 6.8: W/U level as a function of the frequency of the links and the length of the unwanted link in clear sky conditions](image)
Figure 6.9: W/U level as a function of the frequency of the links and the length of the unwanted link in clear sky conditions. Close up for distances between 0 and 10 km.

Similarly, figure 6.10 shows the W/U level as a function of the frequency of the links and the length of the unwanted link during rainy conditions for the same unwanted transmit and receive angle. As in the clear sky case, as the unwanted link length increases, there is a gradual increase of W/U, which is more pronounced for frequencies in the band around 60 GHz. In the rainy case, generally as the frequency of the link increases (with the exception of the 60GHz band), the W/U ratio also increases. Figure 6.11 shows the same graph, but in close up for distances of 0 to 10km.

Figure 6.10: W/U level as a function of the frequency of the links and the length of the unwanted link in rainy conditions (exponential rain model)
Figure 6.11: W/U level as a function of the frequency of the links and the length of the unwanted link in rainy conditions (exponential rain model). Close up for distances between 0 and 10 km.

A direct comparison of figures 6.9 and 6.11 indicates that the W/U is generally higher during rain than during clear sky conditions. This is because the longer the unwanted radio path, the more attenuation it suffers, as seen in figure 6.5. This suggests that clear sky is in fact the worst case for this scenario, and that designing a system with enough margin to cope with clear air effects, which uses ATPC to combat rain fading on the wanted link, will be the most spectrally efficient.

Similar results are seen for different unwanted transmit and receive angles. An example is shown for $\theta$ and $\chi$ both set to 15 degrees in figure 6.12 and 6.13.
Figure 6.12: W/U level as a function of the frequency of the links and the length of the unwanted link in clear sky conditions

Figure 6.13: W/U level as a function of the frequency of the links and the length of the unwanted link in rainy conditions (exponential rain model)

Figure 6.14 shows the variation of W/U with the increase of receive angle for a set unwanted path length of 10km and an unwanted transmit angle of 0 degrees (i.e. the unwanted link is in the same line as the wanted link). Figure 6.15 shows the same variables, but with an unwanted transmit angle of 90 degrees. In both graphs, the effects of the exponential rain model are included.
Figure 6.14 showing the variation of W/U with the increase of receive angle for a set unwanted path length of 10km and a unwanted transmit angle of 0 degrees (exponential model for rain)

Figure 6.15 showing the variation of W/U with the increase of receive angle for a set unwanted path length of 10km and a unwanted transmit angle of 90 degrees (exponential model for rain)

For both figures 6.14 and 6.15 the curves are similar; the only difference is that the W/U is higher when the unwanted transmit angle is higher.
6.5 SPECTRUM EFFICIENCY GAINS RESULTING FROM IMPLEMENTING ATPC

As mentioned earlier, previous and on-going studies have investigated the spectrum efficiency benefits of implementing ATPC in bands up to 38 GHz, primarily concentrating on fixed terrestrial links. In higher frequency bands the situation is complicated by the 10GHz band around 60 GHz, where the oxygen absorption band suppresses long distance transmissions, hence enabling a reduction of the frequency reuse distance to as little as 1 km in some situations.

The link layout scenario presented in this report is by necessity simplistic, dealing as it does with only two links and a simplified rain model. Still the results suggest that ATPC has the potential to improve spectrum efficiency in bands above 60GHz. As a worse W/U is predicted in clear sky than in rain, designing a link to clear sky specifications and compensating for rain fading dynamically on a dB by dB basis will minimise the separation distance between the links.

Further study, similar to that already done in the 38 GHz band (as mentioned in section XX) is recommended to further quantify the potential gains for more realistic rain and link layout topologies.

6.6 SPECTRUM EFFICIENCY GAINS RESULTING FROM IMPLEMENTING DFD

The next section in this report shows how the joint exceedance probabilities of a millimetre wave link and a free space optical link in tandem indicate that deep fading does not happen on both links simultaneously. FSO links are badly affected by fog, and are insensitive to rain, while radio links above 10 GHz are affected by rain but are insensitive to cloud. Hence when the radio path is badly attenuated, the FSO path is not attenuated, and vice versa.

From measurements made at Chilbolton on the 500m range (as mentioned in Section 5.1) to achieve an availability of 99.99% on a FSO link, a fade margin of over 40 dB is required. For a radio link at 57 GHz, a fade margin of ~10 dB would be needed for the same availability. A combined system using both a FSO link and a radio link at 57 GHz would require a 2 dB fade margin on the radio link and a 10 dB fade margin for the FSO link, which is a substantial reduction.

As with ATPC, reducing the transmit power of a radio link during clear sky conditions will improve the rate of frequency reuse within a given geographical area. At this time, effective and economic utilisation of the bands above 60 GHz is believed to be a higher priority, as these frequencies are not commonly used.
6.7 REFERENCES


7 DUAL MILLIMETRE WAVE/FSO SYSTEMS

7.1 INTRODUCTION

Frequency bands above 60 GHz suffer severely from rain attenuation. This will put constraints upon the length or availability of links. Free Space Optical (FSO) systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However, it is speculated that heavy rain and fog/mist rarely occur simultaneously. Therefore, frequency diverse systems, combining mm-wave and Free Space Optical (FSO) systems, have the potential to provide very high availability with reduced interference.

In this chapter we present the analysis of the data collected on the 500 m range at Chilbolton, during the period April 1991 to September 1995. (RA/RAL core project “Propagation above 50GHz”) A previous document discussed the experiment and initial analysis: “Report on the 500m Range Data”, Paulson and Gibbins, June 1991.

Five links were operated along the same 500 m path: four mm-wave links operated at 57, 97, 135 and 210 GHz; and a near optical link at 0.63 μm. Propagation measurements were made by recording on computer the received signal strengths at 10 s intervals, with periodic calibrations carried out by introducing known levels of attenuation into the transmitters.

In this report we investigate the joint statistics of operation of the mm-wave link in combination with the FSO link. These systems use frequency diversity to improve availability. The system includes two links along the same path and carrying the same information, at FSO and a mm wavelengths. As the two system fail under different, and possibly mutually exclusive, meteorological conditions it is hoped that the dual system would have very high availability. To examine this hypothesis, this report examines the simultaneous fade measurements on the 632nm near optical link with each of the mm wave links.

7.2 RESULTS

FSO and 57 GHz

The FSO link and 57 GHz link were both operational for 83.8% of the period 30/4/1992 to 4/9/1995. Figures 7.1 & 7.2 illustrate the attenuation statistics for the FSO link and the 57 GHz link respectively. Y-axis indicates the attenuation threshold that was exceeded for the percentage indicated by the x-axis values. Figure 7.3 shows the joint statistics of the two links. The x-axis and y-axis values of Figure 7.3 indicate the specific attenuation thresholds that were exceeded at the FSO and microwave link respectively for the specified percentages. As the attenuation path was 500m long the attenuation thresholds are approximately 0.5 times the specific attenuation thresholds. For example the specific attenuation at 57 GHz link and FSO link was greater than 2dB/Km (attenuation 1 dB) and 20 dB/Km (Attenuation 10 dB) for 0.001% of the time. In other words when the attenuation at the 57 GHz link was above 1 dB the attenuation at the FSO link was above 10 dB for the percentage of 0.001%. Whereas when the attenuation at the 57 GHz link was above 5 dB the attenuation at the FSO link...
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was above 7.5 dB for the percentage of 0.001%. For the different percentage of 0.010% when the attenuation at 57 GHz was above 5 dB the attenuation at the FSO link was above ~3.5 dB The S-shape cumulative distribution of optical link is due to very high attenuation caused by fog. Optical links in general are not affected by rain (as mm-waves links)

Figure 7.1: Attenuation statistics of the FSO link.

Figure 7.2: Attenuation statistics of the 57 GHz link
Figure 7.3: Joint Specific Attenuation statistics of FSO and 57 GHz links. The contours are at probability exceedance 20, 10, 5, 2, 1, 0.1, 0.01 and 0.001%.

It is clear from figures 7.1 & 7.2 that the FSO link suffered much higher levels of attenuation compared with the microwave link for the same percentages. For example at 1% the attenuation threshold was ~1dB at 57 GHz whereas at the FSO link was ~35 dB. However the joint statistics (see Figure 7.3) indicate that deep fading at the two frequencies did not occur simultaneously, verifying the potential significant increase in availability possible with dual frequency configuration.

Similar conclusions derived from the analysis of 97, 135 and 210 GHz in combination with FSO data.

**FSO and 97 GHz**

Figures 7.4 illustrates the attenuation statistics for the 97GHz whereas the joint specific attenuation statistics in combination with the FSO are shown in Figure 7.5
**Figure 7.4:** Attenuation statistics of the 97 GHz link

**Figure 7.5:** Joint Specific Attenuation statistics of FSO and 97 GHz links. The contours are at probability exceedance 20, 10, 5, 2, 1, 0.1, 0.01 and 0.001%.
**FSO and 135 GHz**

Figures 7.6 illustrates the attenuation statistics for the 97GHz whereas the joint specific attenuation statistics in combination with the FSO are shown in Figure 7.7.

**Figure 7.6:** Attenuation statistics of the 135 GHz link

**Figure 7.7:** Joint Specific Attenuation statistics of FSO and 135 GHz links. The contours are at probability exceedance 20, 10, 5, 2, 1, 0.1, 0.01 and 0.001%.
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**FSO and 210 GHz**

Figures 7.8 illustrates the attenuation statistics for the 97GHz whereas the joint specific attenuation statistics in combination with the FSO are shown in Figure 7.9.

**Figure 7.8:** Attenuation statistics of the 210 GHz link

**Figure 7.9:** Joint Specific Attenuation statistics of FSO and 210 GHz links. The contours are at probability exceedance 20, 10, 5, 2, 1, 0.1, 0.01 and 0.001%.

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7.3 CONCLUSIONS

Frequency bands above 60GHz suffer severely from rain. (Frequencies around 60GHz suffer also from oxygen attenuation which in contrast with rain attenuation is always present). Free Space Optical (FSO) systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However the study of the joint statistics between a microwave and optical link indicates that the deep fading at the two frequencies did not occur simultaneously. This verifies the potential significant increase in availability possible with the dual frequency configuration.
8 DEMONSTRATION AND OPERATIONAL TRIALS OF WORKING SYSTEMS

8.1 INTRODUCTION

The purpose of the Demonstration and Operational Trial was to verify the availability, reliability and performance of millimetre-wave radio equipment in routine production and to consider its economic viability deployed in a commercial environment. For comparative purposes, an FSO link equipment was also deployed in a dual configuration on a parallel path.

OciusB2 hosted the trial at their site in Runcorn, Cheshire; the equipment was commissioned to provide links between the main site and a business park at The Heath. OciusB2 transmitted commercial traffic across both the 64GHz link and the FSO link. Installation and deployment were completed by March 2005 and the operational performance of the links was continuously monitored for system parameter errors and failures through to November.

The trial also enabled a typical set of deployment costings to be generated, and dual mm-wave/FSO link to be bench-marked against other technologies and deployment options for short-range high data applications.

8.2 TRIAL SITE AND INSTALLATION

8.2.1 Location

The selected test site was at The Heath, Runcorn. This site is a managed high-tech research and development campus, occupied by both new and established companies with strong technology roots. Amongst the tenants are chemists and design companies who utilise high speed data connectivity in their daily activities.

Ocius B2 Ltd provide data services across the site.

![Location Image](image-url)
Radio Systems at 60 GHz and Above

The Heath, Runcorn, a fully serviced technology business park.

indicate rooftop terminals

Scale 500m/sq
8.2.2 Installation

The equipment was installed exactly as if deployed on a commercial basis to provide connectivity between two network routers operating at Gigabit and 100BaseT data rates over a distance of approximately 450m in line-of-sight.

Installation was undertaken to mimic practices normally employed in a commercial environment with care being taken to effect an installation without structural damage to the fabric of the buildings.

Mounting detail of link equipment (60GHz radio only)

Connectivity to the equipment is by means of 4 fibre core cable, additional fibre being installed at one end of the link to give access to the internal network. Local mains supply was provided at each end. The cable termination is made within the container box at the foot of the mounting pole at each end of the link.

Views along link path
8.3 DEPLOYED EQUIPMENT AND INSTALLATION

8.3.1 System configuration

The deployed configuration is as shown in the diagram above. Equipment is positioned at two ends of the trial path – A and B. Both ends include laser-driven optical equipment (FSO) with a specified maximum capacity of 100MBps, and millimeter-wave radio equipment (MRE) with a specified maximum capacity of 1GBps. The FSO and MRE equipments at ends A and B are all connected to the OciusB2 internal local area network. The equipments are controlled and monitored by PCs at each end. Two cameras are positioned at end A, and connected to the monitor PC using a 128k VLAN. One camera monitors the status of the equipment at end A, and the other monitors the weather conditions along the link path.

Datasheets of the deployed equipments are reproduced overleaf.
8.3.2 64GHz link equipment

The installation of the radio equipment was relatively simple, making use of internal DC voltage indicator (relative RF power) to peak the alignment. There are no ‘user serviceable’ controls on the radio, making it a ‘Plug and Play’ installation. Obvious care needs to be taken to avoid erroneous alignment on a side lobe.
8.3.3 Free space optical equipment

The FSO required considerable care in alignment even though this is undertaken using an inbuilt alignment telescope. Again no user serviceable controls are required. It was noted the FSO alignment was extremely sensitive, as would be expected. This raised an issue of mounting mechanism rigidity that could impact severely on the ability of an operator to deploy such equipment in a commercial environment where building fabric concerns could arise.
8.3.4 Network monitoring and alarms

As the installation was intended to mimic a commercial deployment, network monitoring was established alongside the rest of the OciusB2 network connectivity to generate alarms in the event of excessive latency and or network link failures.

The network monitoring system is configured to relay any such alarms onward via e-mail to the RAL project engineer in addition to the duty engineer of OciusB2 Ltd.

In order to monitor the system, the links were added to the existing OciusB2 network supervision system, where the following parameters are checked 5 times in every 10 seconds.

- A warning alarm is raised if latency is experienced above 20mS and below 49mS
- A critical alarm is raised if latency exceeds 50mS
- A critical alarm is raised if the circuit fails.
In the event of a failure alarm it was believed necessary to set in place a system to allow examination of weather conditions (during daylight). To that end CCTV cameras were set up to enable real time visibility of both the equipment and the link path. This visual inspection is date and time stamped so that it can be correlated against any physical movement of the equipment and significant meteorological events that could affect the links.

**View Image - Java Mode**

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*Screen grab of CCTV Camera 1 (note FSO link mounted above 60GHz radio)*

### 8.3.5 Weather monitoring

Examination of local weather conditions was limited to examining local statistics retrospectively to any link alarms. Conditions at nearby Liverpool airport were used to give indications of any correlation.
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Screen grab of example weather data

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<td>42 (6)</td>
<td>30.36 (1028)</td>
<td>WSW 6</td>
<td></td>
</tr>
<tr>
<td>3 PM (19) Apr 10</td>
<td>50 (10)</td>
<td>42 (6)</td>
<td>30.38 (1028)</td>
<td>W 8</td>
<td></td>
</tr>
<tr>
<td>2 PM (18) Apr 10</td>
<td>53 (12)</td>
<td>42 (6)</td>
<td>30.38 (1028)</td>
<td>WNW 10</td>
<td></td>
</tr>
<tr>
<td>1 PM (17) Apr 10</td>
<td>55 (13)</td>
<td>42 (6)</td>
<td>30.33 (1027)</td>
<td>WNW 15</td>
<td></td>
</tr>
<tr>
<td>Noon (16) Apr 10</td>
<td>57 (14)</td>
<td>41 (5)</td>
<td>30.33 (1027)</td>
<td>WNW 19</td>
<td></td>
</tr>
<tr>
<td>11 AM (15) Apr 10</td>
<td>57 (14)</td>
<td>41 (5)</td>
<td>30.33 (1027)</td>
<td>WNW 18</td>
<td></td>
</tr>
<tr>
<td>10 AM (14) Apr 10</td>
<td>55 (13)</td>
<td>44 (7)</td>
<td>30.33 (1027)</td>
<td>WNW 19</td>
<td></td>
</tr>
<tr>
<td>9 AM (13) Apr 10</td>
<td>55 (13)</td>
<td>46 (8)</td>
<td>30.33 (1027)</td>
<td>WNW 18</td>
<td></td>
</tr>
<tr>
<td>8 AM (12) Apr 10</td>
<td>55 (13)</td>
<td>46 (8)</td>
<td>30.30 (1026)</td>
<td>WNW 18</td>
<td></td>
</tr>
<tr>
<td>7 AM (11) Apr 10</td>
<td>55 (13)</td>
<td>50 (10)</td>
<td>30.30 (1026)</td>
<td>WNW 17</td>
<td></td>
</tr>
<tr>
<td>Oldest 8 AM (10) Apr 10</td>
<td>50 (10)</td>
<td>46 (8)</td>
<td>30.30 (1026)</td>
<td>WNW 16</td>
<td></td>
</tr>
</tbody>
</table>

Screen grab of example weather data

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8.4 SYSTEM PERFORMANCE

Continuous monitoring of the links was undertaken, allowing any alarms raised to be examined. The units have been operational throughout the study period without any loss of connectivity.

The system alarm parameters were set such that any link failure or packet loss would raise an e-mail alarm to project managers both on- and off-site. It should be noted no such alarms were generated except under test conditions when the links were deliberately disrupted.

In the absence of a link failure or packet loss event, the link margins were assessed by examining the link logs against an extreme weather event. On the 5th July 2005 a severe storm crossed the area and radar plots were obtained of the event. The records of the links were examined to consider any relationship or impact.

Storm radar plot for 5th July 2005

There was no apparent impact on the link performance. However, the system log did show an increase in RTA, which is believed to be related directly to an unrelated and coincidental network traffic increase, not to any deterioration in link performance as no packet loses were recorded.
### Monitoring log extract for 60 GHz and FSO

The commercial trial was designed to validate claims that reliable equipment was commercially available. The trial was not intended to gather or review propagation data – this task was included in sections 2 and 6 of the study. Propagation experiments are deliberately conducted at the margins of link budgets, and data is recorded by accessing signal levels within the test link equipment. In contrast, a demonstration of commercial utility must be operated at a link budget margin which reduces the risk of outage to an agreed low level, and equipment internal signal levels are not available.

Both links (FSO & 60GHz) operated without any failures during the study period and as such offer a practical solution to the operational requirements of rapid deployment and consistent performance.

Examination of the weather events experienced and forecast make it unlikely that any link failures will be experienced without a reduction in link budgets. Alternative sites for installation on the OciusB2 campus were explored but none with longer range were available that would also allow commercial traffic to be passed over the link. Furthermore, as the purpose of the demonstration was to carry commercial traffic, deliberately reducing the link budget to trigger outages would be contrary to the agreement with the traffic owners. The team intends to continue investigating the 60GHz solution beyond the period of the SES study. This will enable more potential outage events to be logged. New equipment is now appearing in the market place and this will also be assessed in the campus environment.

<table>
<thead>
<tr>
<th>Date</th>
<th>5th July</th>
<th>Status</th>
<th>60GHz</th>
<th>RTA</th>
<th>FSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.51</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 143.4dB</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>08.52</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08.58</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 165.7dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>08.59</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09.33</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 116.3dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09.34</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.23</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 124.4dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.24</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.58</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 106.6dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.59</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.28</td>
<td>Alert</td>
<td>Packet Loss 0%</td>
<td>RTA 113.4dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.29</td>
<td>OK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.5 ECONOMICS OF DEPLOYEMENT

The trial objectives included an examination of typical economics of deployment. The installation of commercially available FSO and 64GHz microwave equipment in a parallel configuration across the same path facilitated this. The chosen trial site was a campus environment, where civil construction (including the laying of fibre) was a possible alternative for connecting two routers on the network. The following cost benefit comparison is between the combined FSO and 64GHz microwave equipment costs and the fibre estimate.

Deployment decisions will be based on capacity requirement, capital cost and funding mechanism, ease and speed of installation, and cost of ongoing maintenance.

Both the FSO and 64GHz systems operated satisfactorily: the 64GHz radio system offered the easiest installation/deployment option.

<table>
<thead>
<tr>
<th>Civil elements</th>
<th>Units</th>
<th>Mtrs</th>
<th>£</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bitmac Carriageway</td>
<td>50</td>
<td>75</td>
<td>£3,750</td>
</tr>
<tr>
<td>Bitmac Footway</td>
<td>500</td>
<td>55</td>
<td>£27,500</td>
</tr>
<tr>
<td>Footway boxes</td>
<td>8</td>
<td>230</td>
<td>£1,840</td>
</tr>
<tr>
<td>Fibre</td>
<td>520</td>
<td>15</td>
<td>£7,800</td>
</tr>
<tr>
<td>Install fibre</td>
<td>520</td>
<td>15</td>
<td>£7,800</td>
</tr>
<tr>
<td>Sub Total</td>
<td></td>
<td></td>
<td>£48,690</td>
</tr>
</tbody>
</table>

| Common installation |       |      |      |
| Estimated elements |       |      |      |
| Internal cabling (capped) | 150  | 25   | £3,750 |
| Fibre termination 6core  | 12   | 10   | £120  |
| Materials – Fibre termination boxes | 2    | 25   | £50   |
| Fibre patch cords | 4     | 15   | £60   |
| Sub total     |       |      | 3,980 |
| Sub Total     |       |      | £52,670 |

Fibre cost estimate

In the above table, the sum of £3,980 represents within building connectivity costs which are common to all three options (64GHz, FSO and fibre). The sum of £48,690 represents additional equipment and installation costs were a hard fibre route to be constructed across the site.

As a guide, the 64GHz radio link cost and the FSO link cost were in the order of 30% of the hard fibre link option.

It should of course be noted that this apparent significant saving should be assessed against the system carrying capacity. The actual fibre material cost estimate of £7,800
is significantly less than the current pricing of a radio link and it can theoretically carry significant data beyond the capability of the radio link (1Gbit in the unit deployed).

8.6 TRIAL CONCLUSIONS AND FURTHER WORK

The links were successfully established using conventional installation practices within an enterprise environment.

Both the 64GHz radio link and the FSO link have operated well with no reported link failures over the installed distance of 450m.

Installation issues relate only to the rigidity of the FSO mounting: this could be a significant concern in commercial deployment. The FSO had to be rested and mounted with a very stable structure to ensure that the required line-of-sight path was achieved and not disrupted by winds and/or vibrations.

An operational range of less than 1km for wide bandwidth connectivity using 60GHz radio is practical. Installation is simple and rapid. Such links would appear to have multiple applications in campus networking and ‘last mile’ environments.

Continuing monitoring of link security will be undertaken.

The purchase price of the radio hardware is not the cost driver. The market is starting using this available kit.
9 CONCLUSIONS AND RECOMMENDATIONS

This report contains the results of a work regarding Radio Systems at 60GHz and above. This work includes theoretical studies and literature research regarding applications, frequency sharing and regulation. A commercial millimetre-wave (at 60GHz) & FSO system was operated at Runcorn as a demonstrator of these systems. In addition 4 years’ of existing data from four millimetre wave links and one FSO link has been analysed to provide base-line operational data.

The following conclusions were drawn:

Examination of System Applications in the Bands 60-100 GHz & Identification of Key Obstacles to Band Use

Millimetre wave communications systems at frequencies above 60 GHz have the potential for very high capacities, especially as more than 10 GHz of bandwidth is available in the current frequency allocations.

Spectrum that is not subject to the oxygen absorption effect exhibits behaviour which is broadly similar to spectrum below 60GHz where, in the absence of precipitation fading, the limit of propagation is the horizon.

Specific applications have been identified that require broad contiguous blocks of spectrum e.g. radio transmission of gigabit ethernet services.

Millimetre wave communications applications need to operate over short paths (< 10km) and also need to take advantage of the high antenna gains and directivities, which can be achieved with small antenna sizes (typically 10 < diameter < 30cms).

Two applications have been identified for further study. These are:
   a. Wireless local area networks providing ~1Gbps capacity through millimetre wave access points.
   b. Very high capacity backhaul for either MESH or branch and tree networks, operated in conjunction with very local wireless distribution services at lower frequencies.

The exploitation of these bands requires the development of low-cost RF technology.

At the frequency range 60 – 100 GHz transmitter/receiver technology is reasonably mature and mass-produced systems are commercially available (see sections 3.2.2 and 3.3.2). For example transmitters with 10mW output power and receivers with 10dB Noise Figure are available today to fulfill the radio link requirements for the applications presented in section 2.

Millimetre wave systems are not particularly suited to situations where long range is required e.g. satellite or HAPS systems or where non-line of sight paths are experienced (e.g. personal communications and home networks).
Millimetre wave systems, at ranges of more than 100m, provide a much better quality of service, in adverse weather conditions (rain and fog), than free space optical (infra red) systems.

**Implications of Licensed and Licence-Exempt Use & A survey of International Activity in Bands 60-100 GHz**

Manufacturers are now launching usable product, especially near the oxygen peak at 60GHz. These products exploit USA-FCC rules and provide a range of typically 1km. There is also some activity at higher frequencies with longer range but manufacturers are waiting for orders before committing to production tooling.

European and other regulators are starting to respond, although the response is far from uniform, e.g. between Europe, USA, and ROW. Within Europe some regulators are establishing national regimes, but most have waited for the report of SE-19 (just available as this report was in preparation). There is still a preponderance of formal licensing, but some regulators will adopt a mix of unlicensed and lightly licensed processes.

The bands 59-66 GHz : 71-76 GHz : 81-86 GHz should be opened on a lightly licensed basis so as to satisfy growing demand.

‘Light licensing’ should be adopted. Traditional spectrum auctions have resulted in the bands at 3.5GHz, 10.5GHz and 28GHz being privately owned but not deployed, and no-one from manufacturing or operating industry has made a case for using the same failed mechanisms in the new bands. Nevertheless, QoS requirements for the identified applications require a degree of interference management. This could best be achieved by following the new USA, low-cost, web-based registration scheme.

Due to the nature of the applications and the directivity of operational equipment in this band, there should be no restriction on channel size. 10GB/s radio links would require the full 5GHz spectrum.

In order to obtain the QoS required for the delivery of the identified applications, the power levels given in tables A4.2 and A4.3 of the Draft **ECC Document ECC/REC/(05)07 ‘Radio Frequency Channel Arrangements for Fixed Service System’** should be increased. Suitable limits for power at the antenna port for 1Gb in both the 71-76GHz and 81-86GHz bands are 19dBm for FSK links, and 16QAM links.

There should be no modulation requirements or restrictions. It is believed that BPSK/QPSK will be used in the majority of links due to the link length requirements

TPC should not be mandatory.

Ofcom should maintain an ongoing interest in the development of a Europe-wide regulatory regime in the frequency bands between 60 and 100GHz that is sympathetic to the needs of both operators and manufacturers; and that the development of both regulations and market be continuously monitored throughout 2006.
Radio Systems at 60 GHz and Above

Radio Channel Characterisation

Subject to the use of appropriate directional antennae line of sight paths operated with low levels of multi-path components both in building and out of building.

Operation through glass was demonstrated with little degradation in multi-path behaviour particularly for near normal incidence. Some smooth frequency selective behaviour was observable across the frequency band measured.

Non line of sight propagation was observed to result in a wide spread of delay components of near equal amplitude within a single corridor.

Non line of sight propagation around an obstacle was observed to occur at discreet frequencies across the band measured only. At other frequencies transmission was attenuated.

For outdoor links the strong reflection from adjacent structures must be considered when selecting the antennae and the location of the terminal equipment.

The spectrum Efficiency of Frequency/Power Control & Dual Millimetre Wave/FSO systems

Previous studies have investigated the spectrum efficiency benefits of implementing ATPC in bands up to 38 GHz, primarily concentrating on fixed terrestrial links. In higher frequency bands the situation is complicated by the 10GHz band around 60 GHz, where the oxygen absorption band suppresses long distance transmissions, hence enabling a reduction of the frequency reuse distance to as little as 1 km in some situations.

The link layout scenario presented in this report is by necessity simplistic, dealing as it does with only two links and a simplified rain model. Still the results suggest that ATPC has the potential to improve spectrum efficiency in bands above 60GHz. As a worse W/U is predicted in clear sky than in rain, designing a link to clear sky specifications and compensating for rain fading dynamically on a dB by dB basis will minimise the separation distance between the links.

Frequency bands above 60GHz suffer severely from rain. (Frequencies around 60GHz suffer also from oxygen attenuation which in contrast with rain attenuation is always present). Free Space Optical (FSO) systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However the study of the joint statistics between a microwave and optical link indicates that the deep fading at the two frequencies did not occur simultaneously. This verifies the potential significant increase in availability possible with the dual frequency configuration.

From measurements made at Chilbolton on the 500m range to achieve an availability of 99.99% on a FSO link, a fade margin of over 40 dB is required. For a radio link at 57 GHz, a fade margin of ~10 dB would be needed for the same availability. A combined system using both a FSO link and a radio link at 57 GHz would require a 2 dB fade

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margin on the radio link and a 10 dB fade margin for the FSO link, which is a substantial reduction.

As with ATPC, reducing the transmit power of a radio link during clear sky conditions will improve the rate of frequency reuse within a given geographical area. At this time, effective and economic utilisation of the bands above 60 GHz is believed to be a higher priority, as these frequencies are not commonly used.

*Demonstration and Operational Trials of Working Systems*

Both the 64GHz radio link and the FSO link have operated well with no reported link failures over the installed distance of 450m.

An operational range of up to 1km for wide bandwidth connectivity using 60GHz radio is practical. Installation is simple and rapid, and suitable equipment is commercially available. Such links would appear to have multiple applications in campus networking and ‘last mile’ environments.