Examining the potential to use SHF and EHF spectrum to support Wireless Camera PMSE applications

Spectrum planning for the London 2012 Olympic Games and Paralympic Games

SAGENTIA

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Executive Summary

This report addresses the feasibility of using SHF (3-30GHz) and EHF (30-300GHz) to provide wireless camera connectivity for the 2012 London Olympics and PMSE generally over a longer timescale.

Existing wireless cameras typically use spectrum around 2.3GHz. After an initial analysis of requirements, propagation and equipment availability we focused on spectrum at 7.5GHz and 60GHz. At 7.5GHz the propagation characteristics are not dissimilar to those at 2.3GHz, making this an ostensibly feasible choice. At 60 GHz, propagation is very different, but there is an emerging commercial interest in the band in the USA (for point to point links and personal area networks).

We developed a model to predict the range at different frequencies, talking into account the modulation schemes, link budgets and noise performance that would be expected. Theory suggested that the performance of 7.5GHz equipment at 1W should not be dissimilar to the performance of 2.3GHz equipment at 100mW. However it would be necessary to conduct empirical trials to confirm this.

We researched the applications of wireless cameras and explored the suitability of higher frequencies for each of these applications. We found that there is scope in principle for migrating a proportion of existing usage at 2.3GHz to higher frequencies.

In the case of electronic news gathering (ENG), the need to deploy equipment which will cope with unpredictable ad hoc situations will discourage migration to higher frequencies. However, in outside broadcast (OB) applications, we determined that it would be feasible to implement system architectures which would accommodate the shorter range of 7.5GHz versus 2.3GHz.

We found the greatest opportunity for using 7.5GHz to be in stadium OB applications. Some increase in power will be needed and the number of receive antennas may also need to be increased. But the use of 7.5GHz would allow greater frequency reuse than would be possible at 2.3GHz.

Increased transmitter power and the use of multiple receive antennas may make the use of 60GHz possible within stadia on the back of technology developments at this frequency. It may also be possible to deploy 60GHz line of sight links in mobile OB to helicopter and OB/ENG helicopter to static vehicle applications. Though the activity at 60GHz will undoubtedly start to open up the use of higher frequencies, existing applications are not sufficiently close to those of wireless cameras to make the technologies relevant in time for the London 2012 Olympic Games and Paralympic Games.

Overall our analysis suggests that approximately one third of existing usage could be migrated to frequencies higher than those used at present.

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1 Introduction

This report was commissioned by Ofcom to address the feasibility of using SHF (3-30GHz) and EHF (30-300GHz) to provide wireless camera connectivity for the 2012 London Olympics and PMSE generally over a longer timescale.

Wireless TV cameras are already used extensively for electronic news gathering (ENG) and outside broadcast (OB) purposes and the usage is growing. Current cameras typically operate in allocated PMSE spectrum from 2 to 3GHz. As part of the European 3GSM standardisation a large amount of this spectrum will be unavailable for use by wireless cameras by 2012.

For the 2012 Olympics there will be significant demand because of the large number of broadcasters present as well as the general growth in usage. In addition the trend towards HDTV is expected to increase the spectrum required for these cameras.

Ofcom will organise a full frequency plan for the 2012 Games. Ofcom has identified that there is some SHF spectrum and a significant amount of EHF spectrum available.

This report assesses the feasibility of frequencies higher than 2 to 3GHz being used in future by wireless cameras. ‘Feasibility’ includes considerations of spectrum availability, propagation, equipment availability and technical performance in relation to users’ requirements.

2 The current situation

2.1 Introduction to wireless cameras

2.1.1 Basic description

Broadcast cameras are all made up of three component parts

1. the lens
2. the camera body
3. a connection to the external world (for signals and power).

Costs of wireless camera systems vary but a typical system for Standard Definition television is in the order of £18k for the wireless link plus the costs of camera body (£20k) and lens (£35k).

The connection to the external world which is normally through a cable which is called a Triax because of its construction.

In the case of a wireless camera the lens and the camera body remain, but the connection to the external world is replaced by a wireless transmitter and a battery pack. The wireless transmitter units used in the UK are made by a small number of specialist companies including Link Research and Gigawave.

In addition there are also subminiature cameras which are mounted in Formula 1 cars, motorbikes etc.

2.1.2 Specifications of typical wireless camera transmitters

The specification of two current HD transmitters are given in the table below.

	Link L1403/L1405 HD	**Gigawave HD D-Cam 'Clip-on'**
Frequency Range	1.95 – 2.7GHz 3.4 – 3.58GHz	1.3 – 7.5GHz ('other bands may be available')
Tuning range		300MHz
Channel	10MHz or 20MHz	10MHz
Video encoding	MPEG-2 9-80Mbps	MPEG-2 5-32Mbps
Modulation	DVB T - QPSK / 16QAM / 64QAM LMS-T (proprietary) 10MHz / 20MHz	QPSK, 16QAM, 64QAM
Power output	Up to 100mW	100mW
Antenna	Omni	Omni
Power Consumption:	24W	18W
Dimensions	61 x 206 x 121 mm	160 x 130 x 54 mm
Weight	0.995 kg	0.95 kg

2.1.3 Conclusion

Current wireless cameras use transmitter modules supplied by a very few specialist suppliers. The modules typically deliver 100mW RF within defined bands between 1.3 and 7.5GHz. Power consumption is around 20 to 25W. Their maximum data rate depends on the channel width: up to 40Mbps for a 10MHz channel and 80 Mbps for a 20MHz channel.

2.2 The use of wireless cameras

2.2.1 Overview

Wireless cameras have grown in use dramatically over the last five years; since the development of digital transmission systems. The use of these cameras has allowed the programme producer to obtain pictures from locations where it is physically not possible to cable (e.g. Heathrow Airport) for security or health and safety considerations, or previously inaccessible locations (e.g. inside buildings). The use of wireless cameras is also seen to have improved production values in the coverage of live events; such as sport where a wireless camera is able to follow the action more closely and speedily.

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The camera can is generally 'hand-held'. Wireless cameras are also used mounted in vehicles (e.g. car, motor cycle or helicopter). Where this is the case the power supply and antenna are separated from the camera; this can enable higher transmitter power and/or directional antenna. The signals carried across the RF link include broadcast quality video (SD or HD), audio, talkback and limited camera control signals.

2.2.2 The populations of wireless cameras in the UK

There are two separate uses of wireless cameras – outside broadcast (OB) and electronic news gathering (ENG). While the camera equipment is identical at present, the equipment is licensed differently and owned and operated by different organisations. The table below shows the differences between these two categories of use.

	Outside Broadcast (OB)	**Electronic News Gathering (ENG)**
Examples	<u>Normal events</u> Regular sporting fixtures and cultural events Cathedral services <u>Major events</u> Royal wedding Pop festival Oxford/Cambridge boat race	Rail crash Press conferences
Location characteristics	Defined, pre-determined, space	Ad hoc, where the action is
Time characteristics	Regular peaks of usage, but normally the cameras are spread across different events so there will be less than five at any one 'normal' event. Major events will have more.	Sharp peaks of usage
Predictability	Predictable and pre-planned	Unforeseen, often needs to be set up in a hurry. News organisations race to be first
Licensing	Bookable frequencies allocated on a regional, case by case basis <u>Normal events</u> 260 assignments/month Average use per booking 5.7days <u>Major events</u> Athens 2004 - 101 requests mostly fixed venue across Athens Tour de France 2007 - 30 video camera channels in use	National frequencies allocated on a permanent basis. 2 per user for ITN, Sky, BBC + others 195 assignments/month estimated

We have estimated the size of the populations as follows.

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Outside Broadcast

Owner/Operator	Total number of wireless cameras	Details
BBC Outside Broadcast Operated by BBC Resources Limited	35	• 15 transmitter / receiver low power systems for use with broadcast quality standard definition cameras • 20 super compact low power systems
Charter Broadcast – Hire company Other key hire companies of similar size: Presteigne Broadcast Broadcast RF	21	• 15 transmitter / receiver low power systems for use with broadcast quality standard definition cameras operating at 2.5GHz although some 3.4 and 5GHz operation • 6 (+4 planned) HD systems
Total	56	

Electronic News Gathering

Owner/Operator	Total number of wireless cameras	Details
ITN	12	• 10 receiver / transmitter low power systems for use with broadcast quality standard definition cameras • 2 motorcycle newsgathering systems
Sky News	17	• 11 SNG trucks for Sky News each with radio camera • 2 SNG trucks for CH5 News each with radio camera • 1 Radio links Truck with radio camera • 1 News Bike with radio camera • 1 Hybrid [radio link/SNG] being built • 1 Helicopter with digital link
BBC News	20 estimate	
Total	49 estimate	

(Source: interviews with broadcasters and hire companies)

2.2.3 Other uses

Video Assist - Directors of films need to be positioned very closely to the cameras in order to anticipate the suitability and quality of footage being shot. However in many scenes this is simply not possible, either because there is action and movement or because there are a number of cameras widely spaced to cover different angles.

In these cases *video assist* equipment may be used to bring a TV picture of the film camera's point of view to the director. This can be done with cables but often it is not practical, cables get in the way and can not be used on mobile cameras without causing more problems.

Wireless video camera systems therefore have been used for a few years, but the older analogue type equipment has limitations, in that they really only work well in line of sight applications and they require people to point directional radio antennas in order to get the best results. The newer digital equipment avoids some of these pitfalls.

Security Applications – in addition to the broadcast use of wireless cameras, the our interviews with the manufacturers have indicated that there is a growing use of wireless cameras by the security industry, in particular the police forces. The manufacturers have already begun to receive requests for information from the London Chamber of Commerce and Industry and the Metropolitan Police for wireless security cameras for the London 2012 games.

2.3 Linking wireless cameras with the studio

The signals from wireless cameras need to get back to the studio.

In general there are at least two hops involved. Wireless cameras rarely, if ever, transmit directly to the studio.

It is helpful to separate out the two hops:

- From the camera to an intermediate point
- From the intermediate point to the studio.

The focus of this study is on the first hop which originates at the camera and terminates at an intermediate receiver. However, in practice, the second hop may use the same PMSE spectrum so it is included here for completeness.

2.3.1 Camera to intermediate point

The table overleaf shows different camera situations and intermediate receiver locations.

The signals can operate over distances from a few hundred metres to several kilometres dependent on the power of the transmitter (normally 100mW) and gain of the antennas.

Use	Camera location	Intermediate receiver location	Line of sight currently?	Max distance
OB	Stadium	Base stations in stadium	Normally, but not always 80/20	250m
OB	OB from inside a building	Static OB vehicle (scanner) outside	No, because of walls	200m
OB	OB in open space	Static vehicle eg golf buggy or scanner	Not always, because of obstructions 50/50	1.5km
OB	Mobile OB (motorcycle or vehicle)	Static receive point	No	1.5km
OB	Mobile OB (motorcycle or vehicle)	Helicopter	Normally but not always 80/20	1.5km
OB	Super compact	Cellular base stations arranged along route	Not always	500m
OB/ENG	Helicopter	Static vehicle or fixed receive point	Yes	30km
ENG	Electronic news gathering	Fixed receive point e.g. ENG vehicle	Not always, because some situations may be set up quickly in poor terrain (eg a rail crash)	1.5km

2.3.2 Intermediate point to the studio

There are, again, various options, as listed in the table below.

Use	Intermediate transmitter location	Final receiver location	Type of link (see below)	Line of sight currently?	Max distance
OB	OB vehicle eg golf buggy	OB vehicle	Ground based link	Normally, but not always	500m
OB	OB vehicle	Fixed base station	Ground based link	Normally, but not always	10s of km
OB	OB vehicle	Satellite	Satellite up-link	Yes	100s of km
OB	Helicopter	Static OB vehicle or fixed base station	Mobile link	Yes	10s of km
ENG	ENG vehicle	Fixed base station	Ground based link	Normally, but not always	10s of km
ENG	ENG vehicle	Satellite	Satellite up-link	Yes	100s of km

Ground based Links

Temporary radio link set up as part of the programme chain between the outside broadcast or newsgathering operation and the studio. The link vehicle is usually a stationary car or van with permanent transmitter, power supply and routing facilities. In London there are a number of fixed receiving points e.g. LWT South Bank or the Arqiva Croydon Tower acting as a hub for newsgathering or outside broadcast. While links generally operate line of site, given security and parking restrictions, this is not always possible and sometimes links rely on reflected signals. Ground based links can operate over distances of up to 50km with power levels of around 10 watts and directional high gain antenna. A number of news operations e.g. ITN are beginning to supplement link vehicles with motorcycle-based newsgathering units to enable both fast speed of response and to get around parking restrictions.

Mobile Links

Temporary radio link established between a mobile transmitter and a mobile or fixed receiver. Examples are transmitters on motorcycles, in Formula 1 cars to a helicopter mid-point relaying the signal to a fixed point. Helicopter mounted cameras would also come into this category. The signal is invariably line of site between the transmitter and receiver.

In all of the above the only latency is that associated with signal coding/decoding; path delay is minimal. However both OB's and newsgathering also make use of satellite.

Satellite up-links

Used for both programme contribution between an outside broadcast studio and in Satellite News Gathering (SNG). Satellite up links add around 300msecs of propagation delay.

3 Frequency bands of interest

2.3GHz (2.025 to 2.290GHz)

The baseline frequency band is 2.025 to 2.290GHz. This is already heavily used for wireless cameras in the UK and provides the benchmark against which users will assess the performance of other frequencies. We refer to this as the 2.3GHz band.

7.5GHz (7.110 to 7.425GHz)

The next substantial block of spectrum widely available for wireless camera use is 7.110 to 7.425GHz (the 7.5GHz band). This band has the advantage that the propagation characteristics are not that dissimilar from the 2.3GHz band. In particular, many wireless camera applications are unable to guarantee a clear line of sight path to the receiver and therefore have to rely on reflected signals. At 2.3GHz and 7.5GHz there is still enough reflected signal under most circumstances that communication can be established, and the modulation schemes in use are designed to make this possible. Above 7.5GHz there is less reflection and the modulation schemes are not proven.

The equipment suppliers either already have, or are working on, equipment for this band.

60GHz

60GHz is of interest because it may be possible to exploit technology which is being developed in the USA. In the USA the band is licence exempt and is starting to be used for wireless network extenders and personal area networks (PANs). It is possible that some of this emerging technology could be redeployed in the UK for wireless cameras. Though the range of 60GHz equipment is typically short, and the propagation characteristics are very different, it is considered that the band could offer opportunities for short range links within competition venues (albeit not in time for the 2010 Olympic technology freeze).

In addition to the three bands described above we originally also considered other frequencies from 7.5GHz to 25GHz. For example, 10GHz is just beyond current wireless camera equipment but might be achievable as a 'next step'. However, on balance, we concluded that these frequencies would not offer the propagation characteristics that wireless camera operators require.

4 Modelling the characteristics of wireless camera systems at higher frequencies

4.1 Introduction

The objective of this study is to determine the feasibility of using higher frequencies. We have therefore modelled the range and characteristics of wireless camera links at different frequencies. Unfortunately, to give an estimate of range at any frequency, several design parameters must be decided upon first. The model takes into account the following parameters:

- Gross bit rate
- Transmit power
- System bandwidth
- Frequency
- Antenna gains
- Receiving system noise figure
- Signal to noise ratio minimum for detection (a parameter related to the chosen modulation scheme)
- Fade margin (allows for the presence of destructive multipath interference).

The structure of this chapter is that we present the results first, and then explain them in subsections concerned with each design parameter.

4.2 Results

The table overleaf shows the parameters we have used and the ranges we predict.

Frequency	**2.025 to 2.290**	**7.110 to 7.425**	**60**	**GHz**
Gross data rate	90	90	90	Mbps
TX antenna gain	3	3	3	dB
RX antenna gain	6	6	6	dB
Modulation	OFDM, 64QAM	OFDM, 64QAM	QPSK	
Bits per symbol	6	6	2	bits
Symbol rate	2000	2000	45000000	per sec
Number of subcarriers	7500	7500	1	
Carrier spacing	2000	2000		Hz
System bandwidth	15.00	15.00	90.00	MHz
Distance per symbol	150000	150000	7	m
Minimum signal to noise ratio	20.6	20.6	13.3	dB
Receiver noise figure	4	4	12.5	dB
Fade margin	20	20	6	dB
Range Estimate, 100mW			(Line of sight only)	
With Fade Margin	223	68	15	m
With No Fade Margin	2229	684	29	m
Range Estimate, 1W			(Line of sight only	
With Fade Margin	705	216	45	m
With No Fade Margin	7049	2162	83	m
Range Estimate, 10W			(Line of sight only	
With Fade Margin	2229	684	123	m
With No Fade Margin	22291	6836	211	m

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The table shows the predicted range at each frequency. Ranges are given with and without a fade margin. Figures given with a fade margin would pertain to single receive antenna whereas those without a fade margin would pertain to a diversity or cellular system. Such an arrangement would allow a radio to work up to its sensitivity limits without failing early in localised areas impacted by fading. This would allow a system to be planned to operate up to its sensitivity limit rather than reserving some of the link budget to offset possible fades.

4.3 Data rate

The raw data rate on the wireless link depends on both the data rate from the MPEG-2 codec and the degree of forward error correction employed. Unfortunately, neither of these figures can be specified in definitive terms because they depend on the picture quality and signal robustness being sought.

The data rate from the MPEG-2 codec depends on picture quality. At low data rates viewers can experience coding artefacts resulting from the way the compression is performed. At higher data rates the compression is not noticeable. While typical broadcast HD signals employ below 20Mbps, contribution quality HD signals will require much higher bit rates. The required bit rate also depends on the material being filmed. Ball sports and drama typically require higher bit rates than track sports or news.

Forward error correction adds an overhead of between 50% and 100% to the bit rate from the codec.

For the purpose of this report we have assumed a bit rate equal to the highest employed by current equipment. This is a reasonable assumption because broadcasters are currently at the limits of current equipment and are pushing for the highest quality pictures they can get. The HD equipment from Link Research provides 58.54 Mbps[1] in a dual channel. Using the stated FEC rate of 2/3 we calculate the gross rate as approximately 90 Mbps.

We have had conversations with BBC Research on this topic. Their view is that good quality HD currently needs 60-80Mbps net, but most current equipment in use does not achieve this.

We have used 90Mbps for the purpose of modelling but recognise that it is a conservative figure and that the rate for track sports or news could often be lower than this without any degradation in perceived quality.

4.4 Transmit power

We have modelled systems using, 100mW, 1W and 10W.

Power	Reason
100mW	Standard wireless transmitters from Link Research and Gigwave produce 100mW of RF
1W	1W represents the maximum that could reasonably be produced by a unit sitting directly in the Triax socket. This is the maximum for portable equipment. Link Research supplies a 1W clip-on power amplifier.
10W	This is the power produced by existing outboard amplifiers. Link has a 5W amplifier for use in vehicles and also one in suitcase format. Gigawave supplies 5 and 10W amplifiers. Beyond 10W, health and safety starts to become a concern. So 10W represents a reasonable maximum for mobile equipment.

[1] http://www.linkres.co.uk/assets/documents/support/21/White_Paper_-_Achieving_Performace_for_High_Definition_Video_over_Wireless_Links.pdf

While higher transmit powers offer greater range, there are several factors which limit the achievable power. These include:

(1) Health and safety

Microwave radiation is non-ionising and therefore causes heating when absorbed.

The health and safety aspects of microwave radiation are governed by the Health Protection Agency (HPA). The HPA recommends the guidelines produced by the International Commission on Non-Ionizing Radiation Protection (Guidelines For Limiting Exposure To Time-Varying Electric, Magnetic, and Electromagnetic Fields (Up To 300GHz)[2]).

Below 10GHz the effects are considered to be volumetric whereas above 10GHz the effects are only skin deep. Thus, below 10GHz, there is a limit on SAR (specific absorption rate) whereas above 10GHz the limit is on power density. However, the SAR calculations are complex so 'reference levels' can be used between 2GHz and 10GHz. These reference levels are identical to the levels above 10GHz.

	Microwave frequencies below 2GHz	**2GHz to 10GHz**	**10GHz to 300GHz**
Power density	N/A	Reference level of 50 W/m^2 for occupational exposure 10 W/m^2 for general public exposure	50 W/m^2 for occupational exposure 10 W/m^2 for general public exposure
Localised SAR (head and trunk)	10W/kg for occupational exposure 2W/kg for general public exposure		N/A

Accordingly, for all frequencies covered by this report, the power density limits of 50 W/m2 for occupational exposure and 10 W/m2 for general public exposure apply.

In most situations the greatest exposure will be to the cameraman rather than to the general public. In the case of handheld cameras, the cameraman's head is typically almost adjacent to the antenna. Assuming that the antenna can be re-positioned so that it is a minimum of 10cm away from the cameraman's head, the EIRP would be limited to 6W. If the antenna is omnidirectional with a gain of 3dB as discussed above, the RF power limit would be 3W.

Provided members of the public are 2.25 times further from the antenna than the cameraman, then they will be below the more stringent exposure limit. If we assume that no one would come within 0.5m of the cameraman, then there is a comfortable safety margin.

Link Research has published a document[3] aiming to put current practices in context. It states that the current levels of 100mW have been chosen with safety levels in mind, but also argues that

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[2] http://www.icnirp.org/documents/emfgdl.pdf
[3] http://www.linkres.co.uk/assets/documents/support/10/Health_and_Safety_issues_relating_to_DWCS.pdf

there is a large safety margin incorporated in this figure. This paper assumes the antenna to be 20cm from the cameraman's head. Using this figure, the power limit would rise to 12W.

Taking these limits into account we are confident that a 1W transmitter with a 3dB omnidirectional antenna would be well within health and safety limits and should present no dangers to either the cameraman or the public.

(ii) DC Power

Battery life is a major consideration in wireless cameras. At 100mW the transmitter draws a similar amount of power as the camera, and standard rechargeable batteries allow at least two hours usage. Anton Bauer, one of the main suppliers of batteries for professional equipment, advises that two hours is considered to be the minimum[4].

Transmitters producing 1W will normally require backpack batteries. Transmitters operating at 10W will require large battery banks or generators.

(iii) Heat dissipation

Linear power amplifiers (required for systems employing OFDM modulation schemes) are typically very inefficient and dissipate 95% of the DC input as heat. A 1W modulator and transmitter would produce almost 40W of heat. To cope with this would require either a substantial heat sink or a fan.

(iv) Receiver dynamic range

The greater path loss associated with communicating at higher frequencies means that power levels will normally have to rise to compensate. However, if high power transmitters are close to receivers they will tend to block signals from transmitters which are further away. The maximum power may need to be set with reference to the receiver dynamic range.

4.5 Antenna gains

4.5.1 Transmit antenna

We have used a 3dB gain transmit antenna as our default.

Handheld cameras are, by their nature, moveable, so horizontally directional antennas would be infeasible without stabilisation or beam steering, which in turn would add bulk and weight. So cameras typically have omni-directional antennas. These have a doughnut shaped polar diagram with a 3dB gain in the horizontal dimension.

Vehicle or helicopter mounted antennas may, in some situations, have greater gain and directionality if automatic antenna stabilisation rigs are employed.

4.5.2 Receive antenna gain

As our default we have used 6dB gain.

[4] Anton Bauer Video Battery Handbook, p10. http://www.antonbauer.com/downloads/2002Handbook.pdf

The base unit is likely to be based around the perimeter of a site and will be pointed generally in the right direction. More gain will improve the link budget and range, although it will narrow the beam width and increase the difficulty of alignment.

If we work on the assumption that up to 3 or perhaps 6 dB is achievable whilst maintaining an omnidirectional pattern in two dimensions by compressing the pattern into a 'dougnut' then we can assess the impact of further increases in terms of creating a directional pattern.

- A further doubling of the power is achievable by focusing the power approximately into the forward half of the pattern.
- 6dB should be achievable by focusing the power into a quadrant, ie approximately a 90 degree beam width.
- To achieve a further increase of 10dB, the pattern will take up about 10% of its original 360 degree field of view, ie 36 degrees.

Real antenna design is obviously more complex, but this calculation works on the basis of conservation of power emitted and as such provides a working assumption independent of frequency or design choices (or resulting antenna size).

Looking at the geometry we can see that with a 36 degree beam width and a total gain of 16dB at the receiver end, at the opposite end of the stadium (300m away) the beam should be approximately 200m wide. This implies that more gain than the 6dB default should be possible in many situations.

4.6 Modulation parameters

Modulation schemes

As the modulation used will strongly impact the behaviour of any wireless system, it requires careful consideration when changing the RF frequency of wireless camera systems.

Many different radio modulation schemes have been developed over the years to meet different needs. Original analogue modulation schemes such as FM voice modulation or amplitude modulation (AM) have been replaced by digital schemes such as frequency shift keying (FSK) and amplitude shift keying.

As more applications have arisen which intensify the need for fast data throughput and optimal use of scarce spectrum, higher order modulation schemes have been developed. By putting more 'bits' of data into each modulation symbol, more data can be pushed through the same channel. This increases the spectral efficiency, but all other things being equal, the range and robustness is reduced. This is because a higher signal to noise ratio is needed to decode a higher order modulation scheme in the presence of noise. Examples of higher order modulation schemes are Quadrature Phase Shift Key (QPSK) at two bits per symbol, and 16 or 64 Quadrature Amplitude Modulation (QAM) at 4 and 6 bits per symbol.

Modulation and inter symbol interference (ISI)

For a given modulation scheme, as the data rate increases, the bandwidth requirements go up, and the symbol period decreases.

For QPSK (2 bits per symbol) at 1Mbps the symbol rate is 500kS/s. This means each symbol lasts for two microseconds. Light travels about 600m in this time. For long range systems where multipath signals might bounce from objects 300m away, the result could be inter symbol interference. Some energy from the previous symbol arrives during the current symbol, causing errors. These errors are non Gaussian and cannot be mitigated simply by increasing transmit power.

If the data rate increases to 100Mbps, the RF differential path length for ISI becomes 6m, (ie a reflection from an object just 3m away).

Note that this calculation is for an entire period of ISI for illustration – lesser delays can also contribute to bit errors.

Clearly for Gbps systems using QPSK the problem becomes acute – many copies of the signal will arrive from different paths having travelled many multiples of the ISI period causing significant ISI.

However, increasing the modulation scheme order to 6 bits per symbol, 64QAM for example, reduces the ISI sensitivity period (and hence the relevant differential paths that can cause it) by a factor of three.

To do better than this, a system called OFDM is used.

OFDM modulation

RF propagation fluctuates wildly in real world conditions. Signals at one position can be a thousand times lower than at an adjacent location due to the coherent interference between multiple propagation 'rays'. One result of this is the need to reserve 20 or 30dB of an RF system's link budget from the propagation planning to cater for these 'small signal' behaviours.

Another result is that for high data rate signals the channel cannot be assumed to be flat within the bandwidth used. In the same way as one physical location can be subject to a null compared to an adjacent location, so can one frequency be subject to a null compared to an adjacent frequency.

OFDM includes channel equalisation which helps to mitigate for this channel behaviour.

OFDM involves placing many carriers in close proximity to each other and modulating each with a part of the overall data stream. It works because each carrier is placed at the location of a null in its neighbouring carrier such that they shouldn't interfere with each other.

Each carrier can be demodulated independently of the others (although practically this is done for all carriers at once after digitisation using an FFT process). Channels with errors can be tolerated on the assumption that a suitable coding scheme is used, and an uneven channel can effectively be equalised.

Each carrier can be modulated with FSK, QPSK, 16 or 64QAM as desired.

So, if we chose to divide a 100Mbps stream by 50 carriers each carrier would support 2Mbps. If we chose to modulate each with 16QAM, a 4 bit modulation scheme, we can see that the symbol period is 500kS/s and, rather than worrying about reflections from 6m away, we are back to 600m.

In summary, OFDM reduces ISI and increases tolerance to uneven channels, both of which are afflictions that get worse as the data rate rises. OFDM can work with various other modulation schemes to provide a scalable throughput in the presence of greater or lesser channel noise.

This is why WLANs and indeed ADSL data rates drop as the range increases. The carriers are dropping back through the modulation orders.

As seen from the basic phase noise estimation of an oscillator, as the frequency of an oscillator increases, so does its phase noise emissions. We've estimated that the phase noise begins to limit the highest order modulation schemes used in DVB-T to around 20GHz.

As the noise in the channel is Gaussian, the probability of error is related to the cumulative density function of a Gaussian distribution. For FSK, as long as the noise voltage is below half the peak demodulated signal voltage, the bit will be correctly decoded.

For QPSK the number of possible symbols is higher so the RMS error has to be lower in proportion to the carrier. For 64QAM, the allowable RMS error is lower still.

4.6.1 Choice of modulation scheme for each frequency

VCO Phase noise from OFDM Model

The phase noise emitted by an oscillator is important because, if high enough, it can add enough noise to the transmitted waveform to prevent error free demodulation. This can limit the use of higher order modulation schemes which require higher S/N ratios.

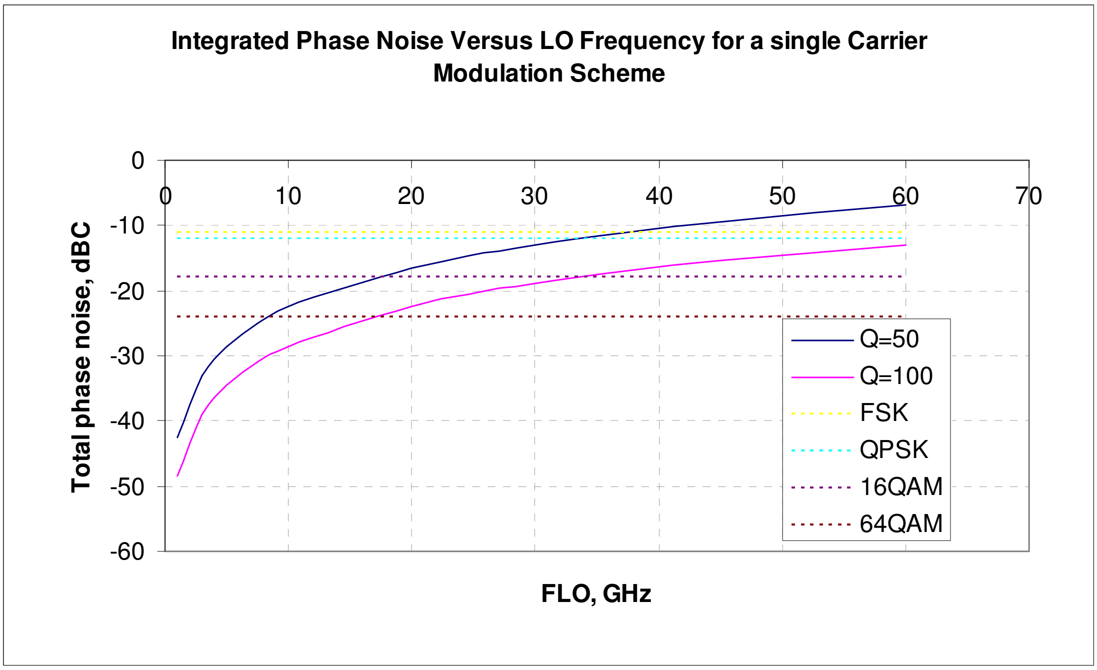
We modelled the total phase noise for oscillators at different frequencies and Qs[5]. This analysis has shown that the higher order modulation schemes will drop away at higher frequencies of the local oscillator.

Note that the model assumes no benefit from phase locking the oscillator. It becomes more difficult to design phase locked oscillators at higher frequencies, although there is some evidence of such devices being used up to 60GHz.

The relationship between the frequency of the LO (Local Oscillator) and the frequency of radio emissions frequency varies with design. We have assumed that the highest frequency oscillator dominates the phase noise added to the signal, and that it operates at a frequency of half the RF emission.

Plots are shown below for a single carrier system, and an adapted plot to account for the phase noise multiplication coming about due to the mixing of the LO with each of the OFDM sub carriers.

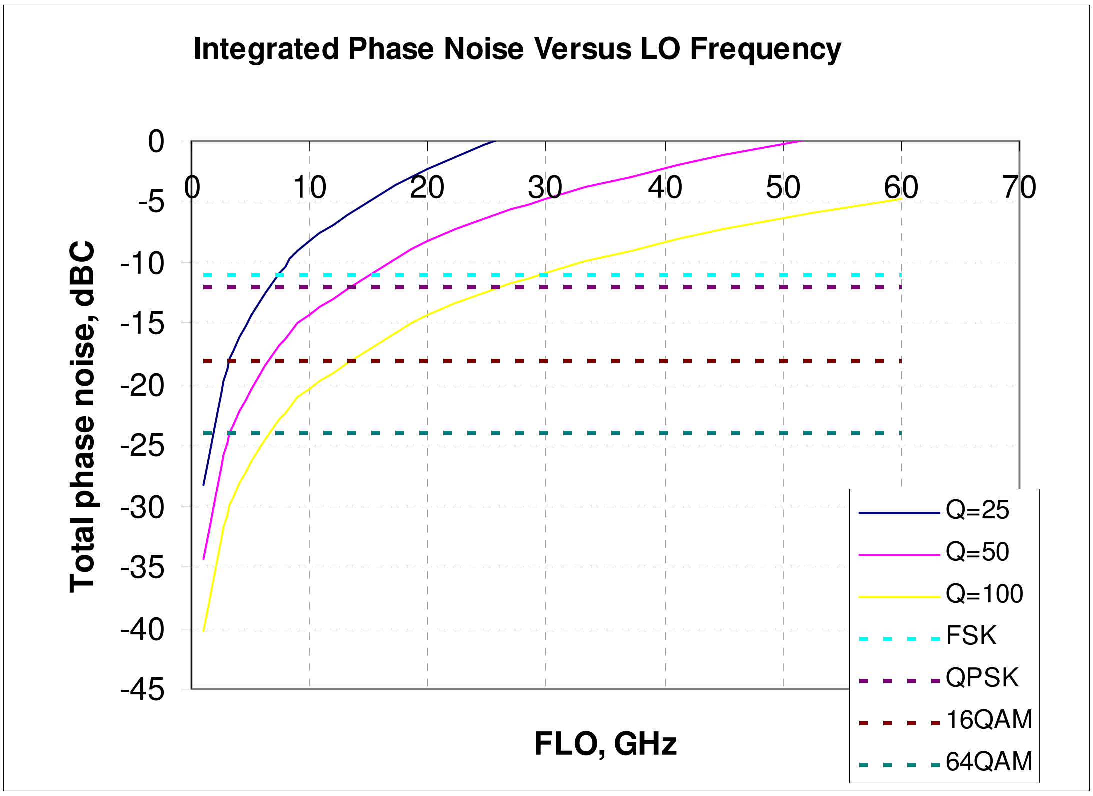
[5] Using $L_{\Delta f} = \frac{2FkT}{Q^2 P} \cdot \left(\frac{f}{\Delta f} \right)^2$



Plot of Phase Noise versus Frequency of Local Oscillator Assuming Single Carrier Modulation

Single Carrier Phase Noise and Modulation Compatibility Table

	Q=50	**Q=100**
FSK	39GHz LO	>60GHz LO
QPSK	34GHz LO	>60GHz LO
16QAM	18GHz LO	35GHz LO
64QAM	9GHz LO	18GHz LO



Plot of Phase Noise versus Frequency of Local Oscillator Assuming OFDM Modulation

Phase Noise and OFDM Modulation Compatibility Table

	Q=50	Q=100
FSK	16GHz LO	32GHz LO
QPSK	14GHz LO	27GHz LO
16QAM	7GHz LO	14GHz LO
64QAM	4GHz LO	7GHz LO

Depending on the Q realisable in the oscillator, and also the benefits if any (none assumed) from phase locking the oscillator to a low noise reference, the phase noise contributed to the signal begins to limit the modulation scheme at a certain frequency.

Conclusion Table for Modulation Versus Phase Noise of Local Oscillator, for the highest RF frequency that can be supported on each modulation scheme

Modulation	FSK	QPSK	16QAM	64QAM
OFDM	32GHz	28GHz	14GHz	8GHz
Single Carrier	78GHz	68GHz	36GHz	18GHz

This table shows the RF frequency of operation that a modulation scheme is predicted to work up to. It assumes a Q of 50 and the numbers are given in GHz. The table has been used to determine the modulation schemes at each frequency.

4.7 Noise and fading parameters

4.7.1 Minimum signal to noise ratio

Digital signal errors are called bit errors. If we consider that noise is typically Gaussian, and we have a channel with a signal voltage and a noise voltage, there is always a probability that the noise voltage (which is asymptotic – the familiar bell curve) can cause a bit error. However as the amplitude of the Gaussian noise increases, the probability of the errors occurring increases quickly.

We have assumed that a physical layer bit error rate of 10^{-6} will be required. The forward error correction will then produce a resultant bit error rate of at least 10^{-9}, which is considered acceptable for MPEG-2.

The required Eb/N0 for a 10^{-6} BER have been obtained from published sources[6]. The Eb/N0 figures were converted to signal to noise ratios using the formula

SNR = 10 log (Eb/N0*data rate/bandwidth).

4.7.2 Fade margin

The requirements for fade margin at different frequencies is best addressed empirically and is an area of ongoing research by many contributors, largely driven by the 60GHz licence exempt spectrum availability in the USA.

6 http://www.ee.ccu.edu.tw/~wl/ofdm/pdfnew/chapter%203%20OFDM%20transmission%20over%20gaussian%20channel_modify.pdf

Fading occurs mainly because of reflections. A surface with imperfections will act like a plane reflector at wavelengths much longer than the surface detail scaling. At frequencies shorter than this, the surface will scatter the signal which will cause much greater overall attenuation of the reflection power and therefore lower multipath. At 60GHz the wavelength is half a centimetre. The texture on a brick wall will be enough to scatter the incident RF power rather than cause a plane reflection. Thus, reflections will tend to scatter the signal incoherently at higher frequencies.

Furthermore, there is higher absorption of energy by materials at the higher frequencies in the range under discussion.

Taken together, these factors lead us to the conclusion that the fade margin can be lower at 60GHz. 20dB is the typical fade margin at 2.3GHz but we have reduced the fade margin in our model to 6dB at 60GHz.

The quality of the video from the camera must be similar to that from a wired camera. One way of getting around the problem of fading is to use multiple receive antennas in a diversity or cellular arrangement. If the signal at one antenna is poor, it is likely that the signal at other antennas is good.

4.7.3 Noise figure

The noise figure of a receiver is a measure of the noise it adds to a signal. The lower this figure, the better. The noise figure of a receiver is dominated by the performance of the first stage, the low noise amplifier.

Low noise receivers depend on design techniques and components optimised for noise. Because there is less equipment at the higher frequencies we expect design techniques to be poorer. There is less demand for components, too, so components will tend not to be as good. Our assumption is that receiver noise will worsen with frequency as per the table below.

Low noise amplifiers are available using Gallium Arsenide at 2.5GHz with noise figures below 1dB. At this frequency the overall noise figure is typically 4dB. This is derated to 12.5dB at 60GHz in the following way, due to the increased difficulty of building gain blocks at higher frequencies.

FrequencyGHz	**2.025 to 2.290**	**7.110 to 7.425**	**60**
Noise Figure	4	4	12.5

MACOM has a low noise amplifier working up to 3GHz with a 0.7dB noise figure, and has parts that operate up to 12GHz at 2.2 dB noise figure. Recent papers presented discuss LNAs at 60GHz with 4.5dB and an LNA and mixer front end combination with 12.5dB at 60GHz.

4.8 Propagation path

Below 7.5GHz the propagation path can be obscured.

Above 7.5GHz there must be a line of sight path.

A key factor in microwave communication systems is whether there is a line of sight path between the transmit and receive antennas. In current usage, the path between the camera and receiver is often obscured. This can arise where the camera is inside buildings, or in remote newsgathering applications in urban environments, or in rough terrain. In such situations, current equipment is still able to communicate. This is because the transmitted signal is refracted and reflected by objects so that some portion of the signal is able to get through. The reflected and refracted signals arrive with a phase delay, however. The modulation scheme currently used is OFDM which is able to recover the information despite of phase delays. Thus, current wireless cameras are able to operate in some situations where there is no line of sight.

The ability to do this decreases with frequency. This is for three reasons:

- A higher frequency signal is more prone to being absorbed or scattered rather than being coherently reflected
- The refracted signal is weaker at higher frequencies
- OFDM modulation, which is able to cope with reflected signals better than most modulation schemes, is less able to work at higher frequencies owing to inherent noise in the oscillators.

Though there is no hard and fast cut-off point it is widely accepted that above about 7.5GHz there is a need to have a line of sight path whereas below 7.5GHz the path can be obscured.

In some circumstances it is possible to 'work around' the lack of a line of sight path by installing additional receive antennas. For example, a stadium could potentially have many antennas around the periphery so that if the signal to one antenna was blocked, another antenna could nonetheless receive the signal.

Ways in which the environment affects propagation include

Shadowing

Objects in the path can obscure the direct line of sight and force the link to rely on the mechanisms of reflection or refraction to couple energy from transmitter to receiver. These mechanisms behave differently at different frequencies.

Reflection and refraction

Just like with optical wavelengths, radio and microwave signals are affected by dielectric discontinuities. Signals can be bent and reflected. In urban environments reflections occur from the surfaces of buildings and vehicles. Refraction occurs from woodland and foliage and from knife edges such as tall buildings. Refraction also occurs from strata in the atmosphere. This feature is often used by Radio Amatuers to communicate far beyond the line of sight horizon in the presence of suitable atmospheric conditions.

Absorption and attenuation

Absorption occurs in the atmosphere at all frequencies, but is not a dominant characteristic at most frequencies. Certain frequencies, including about 8GHz around 60GHz, suffer more pronounced absorption due to interactions with the atmosphere.

Absorption also occurs in materials. Walls strongly attenuate signals (as well as causing reflections) as do plants and people.

Multipath

Multipath is the term for localised spots of low signal strength caused by coherent combination of multiple copies of a signal that have arrived at the receiver via different propagation paths. These signals can combine positively if in phase, to create a slightly higher receive signal strength. They can combine destructively if out of phase to locally reduce the signal power by a factor of a hundred or a thousand.

4.9 Calculations in the model

Free space loss = 32.4 + 20Log F(MHz) + 20Log R(Km)
Atmospheric absorption adds 15dB/km at 60GHz

Path loss

This is a function of frequency and range. Doubling frequency increases path loss by 6dB, equivalent to halving the range if all other parameters are kept the same.

Absorption

At frequencies up to 40GHz, atmospheric absorption is less than 0.2 db/km. There is a water absorption peak around 25GHz included in this figure. On long range radio systems, this is significant, but on links 1km or less, it is not. At 60GHz, there is an oxygen absorption peak of 15dB/km loss. This would be significant on 1km links, but for in stadia use with links of 200m or less this would not be significant.

Rain

Additionally there is a rain related component to the atmospheric absorption that is frequency dependent. Up to 7.5GHz this is <1dB/km for heavy rain and not likely to be significant for links up to 1km. This increases to around 5dB/km at 15GHz, which again should be manageable for 1km links and can be around 20dB/km at 60GHz. This is highly dependent on the level of rainfall – the numbers quoted are for heavy rain, tropical downpour will be higher. Normally a statistical rainfall model is assumed which is used to define a particular availability for the radio system. As the use here is intermittent, it may be more appropriate to consider the level of rain in which the system will be required to work and then design the system to that.

5 Implications of increasing RF power

We have undertaken a modelling exercise to predict the DC power requirements for a given RF output

	100mW	**1W**	**10W**
Camera	20W	20W	20W
Modulator and 100mW amplifier	20W	20W	20W
Additional power amplifier		20W	200W
Total power	**40W**	**60W**	**240W**
Battery capacity for 2 hours	80Wh	120Wh	480Wh

This suggests that, in many situations, the extra battery capacity to increase power to 1W would be feasible. However increasing the power output to 10W will require six times the battery capacity, which is unlikely to be convenient in a handheld camera system.

Increasing output power creates some problems of heat dissipation. For reasons of linearity, current power amplifiers at 2.3GHz are only 5% efficient. 95% of the DC input is dissipated as heat. Taking into account the modulation circuitry as well, a 1W transmitter will dissipate 39W. Removing the heat will typically require either a large heat sink or a fan. These will in turn increase the bulk and mass of the equipment.

At 60GHz, the simpler modulation schemes would not necessitate such linearity and the amplifiers would therefore be more efficient.

Our conclusion is that raising RF power levels to 1W is not without problems but is generally feasible.

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6 Assessment of the feasibility of moving to higher frequencies

6.1 Summary of frequency bands

We have split our discussion into spectrum bands.

7.110 to 7.425GHz

Below 7.5GHz, similar performance to existing 2.3GHz systems can be achieved, but to do this requires higher power levels.

In comparison with 2.3GHz:

- Propagation characteristics remain similar
- Modulation schemes remain similar
- At 7.5GHz, the range at a given power level is reduced to approximately one third of its range at 2.3GHz.
- To compensate for the reduced range, power levels will need to be increased. To achieve an equivalent range at 7.5GHz would require a ten-fold increase in power over a transmitter operating at 2.3GHz.
- Equipment is currently or likely soon to be available from existing suppliers such as Link and Gigawave.

60GHz

Above 20GHz the range is insufficient for wireless cameras in their current modes of use, and apart from the special case of 60GHz the equipment is insufficiently advanced to make systems feasible in the medium term.

The established component base is much poorer than below 20GHz although there are some components becoming available at 60GHz.

- Propagation is restricted to line of sight
- Currently used modulation schemes do not work.
- The range becomes too short to be usable in most applications
- Wireless camera equipment is not available.

6.2 Potential for each application

The following table shows the result of screening each class of application (see section 2.3.1) for the characteristics of the frequency bands discussed above. For those applications for which a higher frequency appears feasible we have indicated where we have investigated further by attempting a ‘strawman’ system design.

Use	Camera location	Intermediate receiver location	Line of sight currently?	Max distance	Feasibility of 7.110 to 7.425GHz	Feasibility of 60GHz
OB	Stadium	Base stations in stadium	Normally, but not always 80/20 Strawman 1	500m	Should be possible with sufficient receive antennas and/or increased power	May be possible with sufficient receive antennas and increased power
OB	OB from inside a building	Static OB vehicle (scanner) outside	No, because of walls Strawman 2	200m	May be possible with increased power	No: Non line of sight
OB	OB in open space	Static vehicle eg golf buggy or scanner	Not always, because of obstructions 50/50 Strawman 3	Up to 1.5km	May be possible with sufficient receive antennas and/or increased power	No. Range too great
OB	Mobile OB (motorcycle or vehicle)	Static receive point	No	1.5km	No: Non line of sight	No: Non line of sight
OB	Mobile OB (motorcycle or vehicle)	Helicopter	Normally but not always 80/20 Strawman 4	1.5km	May be possible with high gain antennas and increased power	May be possible with high gain antennas and increased power
OB	Super compact	Cellular base stations arranged along route	Not always	500m	No: Insufficient range. No opportunity to increase power owing to battery size and weight	No: Insufficient range. No opportunity to increase power owing to battery size and weight
OB/ENG	Helicopter	Static vehicle or fixed receive point	Yes Strawman 5	Up to 30km	May be possible with high gain antennas and increased power	Reduced range may be possible with high gain antennas and increased power
ENG	Electronic news gathering	Fixed receive point e.g. ENG vehicle	Not always, because some situations may be set up quickly in poor terrain (eg a rail crash)	1.5km	May be possible in some situations where the distances are short enough, but not generally applicable	No: Insufficient range and coverage

This first cut analysis suggests that:

- Frequencies around 2.3GHz will still be needed for situations where the power output is limited, where the propagation path is poor, and over long distances.

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- Frequencies up to 7.5GHz will be suitable in many situations, but will often require higher power transmitters and/or more receive antennas.
- At 60GHz, only line of sight applications will be feasible. These may not be naturally line of sight, because in a known environment such as a stadium it is possible to install several antennas in a diversity or cellular arrangement.

6.3 Strawman system designs

6.3.1 Strawman 1: Stadium application

The table below outlines some possible arrangements to cover a stadium of 200m by 300m.

	Existing 2.3GHz	**7.110 to 7.425GHz**	**7.110 to 7.425GHz**	**60GHz**
Tx power	100mW	1 W	0.6W	1W
Number and type of rx antennas	2 180 degree beam	2 180 degree beam	4 90 degree beam	16 23 degree beam
Limitations				Line of sight Restricted coverage

Where multiple receive antennas are indicated, multiple base stations would be installed in the stadium. Depending on the location of the camera, it must 'attach' to one or another base station. If the camera moves out of range of one base station during use it must seamlessly transfer to the new base station. Cellular systems achieve this by having adjacent base stations on different frequencies in what is called a cellular frequency re-use pattern. Ideally the connection would be made with the new station before it is broken with the old one.

For the 7.5GHz arrangement there is a choice between 1W transmitters and two receive antennas, and approximately 600mW transmitters and four receive antennas each with greater directionality. This should behave similarly to 2.3GHz systems.

60GHz might be possible using a large number of base stations. The range might still be too low to achieve full coverage however.

6.3.2 Strawman 2: Outside Broadcast from inside buildings and Electronic News Gathering

We have looked at a point to point system at 7.5GHz. With an omni antenna on camera and a single 15dB directional receive antenna on the scanner, then raising the power of the transmitter should achieve comparable performance to 2.3GHz in most situations. However there will be greater absorption from building elements so the system will not be quite as robust.

6.3.3 Strawman 3: Outside Broadcast in open space

Raising transmit powers to 1W should provide comparable performance at 7.5GHz with a degree of tolerance to obstructions.

6.3.4 Strawman 4: Mobile Outside Broadcast to helicopter

Assuming point to point links with directional antennas, 10W transmitters and automatic antenna stabilisation, the range should be adequate. However line of sight cannot be guaranteed, so 7.5GHz is probably the maximum frequency that can be used.

6.3.5 Strawman 5: Helicopter to static receive point

Assuming point to point links with directional antennas, 10W transmitters and automatic antenna stabilisation, the range should be adequate at the frequencies under consideration.

7 Equipment availability

7.1 Discussion

This report has shown that, in principle, wireless cameras should be able to operate as effectively at higher frequencies than they do now in many situations. This chapter investigates the feasibility of creating equipment within a timescale set by the 2012 Olympics.

Implications of the timescale

The 2012 Olympics will be subject to a 'technology freeze' in 2010. Thus, there is between two and three years to develop, design and produce any new required equipment. This leads us to consider:

- **Components**. For equipment to be ready by then, it is reasonable to assume that the critical components must either be in production already, or be well on the way. Components that are still at the research stage will not be available in time. The critical components include semiconductors for amplifiers, mixers and oscillators.
- **Skills**. Equipment manufacturers will need develop design skills for the new frequencies, which depending on the frequency, can be skills that few radio design companies have access to.
- **Standards**. New standardised modulation schemes, or perhaps modified versions of today's DVB-T, must be agreed if standards are to be followed which would be advantageous to the industry. Indeed standardisation is essential if equipment is to be shared at a stadium.

Components

The critical components are the semiconductors (transistors, FETs, ICs). Wireless cameras are a relatively small market which would not support the development of new semiconductors. Thus the components would need to be off the shelf items already being produced for other markets. The main activity at these high frequencies has been in radar and military applications. Some components and modules exist at these frequencies. Semiconductors produced by such companies as M/A com (Tyco)[7] and MwT[8] are mostly specified to work below 20GHz. Off the shelf amplifier modules are available to 20 or perhaps 30GHz, as well as mixers and oscillator modules based on diodes and transistors. The company Terabeam-HXI produces modules up to above 70GHz but these are designed for military applications and may not have the best characteristics for wireless cameras.

In summary there is a vast difference in maturity between different frequencies in our range of interest but overall it seems that there are more components available below 20GHz than above.

Skills

Design at 2.5GHz is already tricky compared to lower frequencies. Lumped elements (ie capacitors and inductors) become difficult to use due to the low values and high parasitics (in effect each component placed is a network, with the parasitic elements always working against the designer). However it is still possible to build circuits on standard PCB materials and with lumped elements and some transmission line techniques. By 5GHz the problem is worsened but in

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[7] http://www.macom.com/Products/RFMicrowave/default.asp
[8] http://www.mwtinc.com/PDFs/Short%20Form%20Selection%20Guide.pdf

principle, a designer experienced at 2.5 can work at 5GHz. By 10GHz techniques are very different. Microwave circuits are built on ceramic substrates and few lumped elements can be used. The package interconnections can limit performance and so many circuits are built into microwave modules on a common substrate, with die level devices becoming used. The basic building blocks of all circuitry, transistors, are readily available and so fundamentally all the same kinds of circuits can be built, however it should be clear that there is a barrier associated with tools, processes and know how between 5GHz and 10GHz.

Above 20GHz, some transistor designs cease to provide much gain. The upper frequency response can be inversely proportional to the size of an active region, which means that as the frequency response rises the internal dimensions can shrink (at 60GHz a full wavelength is just 5mm). A structure of 1% of that, 50um, will not necessarily act on a signal in a predictable way because the signal will vary across its active region.

This is not intended as a technical assessment of high frequency silicon design, however it should be seen that there is a second barrier to adoption between 20GHz and 60 as the active devices themselves become difficult to build, and having lower internal dimensions, tend to have lower power handling capabilities.

In summary, the techniques of circuit design and construction used by a company working at 2 to 3GHz become progressively less relevant above 10GHz. Above 10GHz circuits need to be designed along different principles. A company that has the skills to design and construct circuits at 2.3GHz should be able to uses the same skills up to 10GHz, but not beyond. Accordingly we judge that 10GHz is a realistic upper limit that current camera equipment suppliers could reach by the Olympics .

Standards

Much of the work in this report is closely coupled with the modulation schemes used for the transmission of data. As in DVB-T, an OFDM scheme with 1kS/s is a baseline assumption but examination of high frequency oscillator phase noise has indicated that the S/N ratios required by this arrangement may not be met at higher RF frequencies. There is at the very least a probability that modifications will be required to the modulation schemes used in DVB-T or that perhaps an entirely new modulation system may be required. OFDM may have to be dropped, bandwidth may increase, modulation order may drop and coding schemes may have to make up for some of the robustness lost.

If standards need to be changed, then agreement between the organisations involved must be found on the right solutions. A sensible precursor to this is the development and use of prototype equipment and first hand knowledge of its behaviour in the field.

60GHz

We searched for design information about 60GHz parts. Rather than finding the same kind of information that would allow a designer to, in effect, start work, what we found was a large number of research papers putting forward architectures for designs and documenting laboratory measurements for those designs. These may be advertising the vendor’s cutting edge process or patenting a novel arrangement.

This activity at 60GHz might introduce new options – though probably not before 2010. In the USA, point to point links at 60GHz are being marketed as network extenders (linking two buildings, for example). Though these only use low power (~10mW) they have very high gain antennas[9]. It is likely that they use simple modulation schemes such as FSK.

[9] http://www.terabeam.com/downloads/specsheets/GigaLink_Series.pdf

Also in the USA there is interest in 60GHz Personal Area Networks (PANS) at 60GHz. This technology is standardised as IEEE 602.15.3. We are aware of chipsets being developed by IBM, Toshiba, Atheros and Intel. The application is for very short distances (in a large office room).

Though the activity at 60GHz will undoubtedly start to open up the use of higher frequencies, we do not think the existing applications are sufficiently close to the wireless cameras to make the technologies relevant within the short term.

7.2 Equipment suppliers' plans

We contacted the two UK wireless camera manufacturers – Link Research and Gigawave. Owing to the competitive nature of their industry they were reluctant to disclose their future plans.

8 Conclusion: How much current use at 2.3GHz can realistically be migrated to higher frequencies?

The range model and strawman exercise has shown that there is scope in principle for migrating a proportion of existing usage at 2.3GHz to higher frequencies.

While in some situations it may be possible to use higher frequencies, it is necessary to think of the practicalities. An OB or ENG unit will not generally go to a location armed with an array of different transmitters in order to select the highest frequency that will work. So in most situations they will want a transmitter that can be relied upon to perform well in different scenarios. Existing 2.3GHz equipment fulfils this need rather well.

In the case of ENG, the need to deploy equipment which will cope with unpredictable ad hoc situations will probably discourage migration to higher frequencies. Thus we judge that ENG will remain at 2.3GHz.

In OB applications, the line of sight limitations of frequencies above 7.5GHz mean that most migration will need to stay below 7.5GHz. Theory suggests that the performance of 7.5GHz equipment at 1W should not be dissimilar to the performance of 2.3GHz equipment at 100mW. However it would be necessary to conduct empirical trials to confirm this.

In the case of stadium OB applications, we have found the greatest opportunity for using 7.5GHz. Some increase in power will be needed and the number of receive antennas may also need to be increased. The use of 7.5GHz would allow greater frequency reuse than would be possible at 2.3GHz.

While there may also be scope for using other frequencies between 10 and 25GHz in some situations, the cost of purchasing equipment for relatively rare circumstances will discourage both broadcasters and suppliers from investing. Point-to-point links can use higher frequencies – as they sometimes do at present. This includes helicopter links, provided automatic antenna stabilisation is employed.

It is not possible to be prescriptive about the proportion of use that can be migrated but an approximate calculation is given below:

- ENG – accounts for 50% of existing cameras – no migration (other than for line of site helicopter to static vehicle OB/ENG links)
- OB inside stadia or other venues – estimate 25% of existing cameras - 100% migration to 7.5GHz or above
- OB in open air and point to point - estimate 25% of existing cameras – 50% migration to 7.5GHz or above

Our analysis has shown that the majority of outside broadcast applications could be migrated to 7.5GHz, and that some line of sight outside broadcast applications could also be migrated to much higher frequencies. Increased transmitter power and the use of multiple receive antennas may make the use of 60GHz possible within stadia on the back of technology developments at this frequency. It may also be possible to deploy 60GHz line of sight links in mobile OB to helicopter and OB/ENG helicopter to static vehicle applications.

Overall, our analysis suggests that approximately one third of existing usage could be migrated to higher frequencies.

Though the activity at 60 GHz will undoubtedly start to open up the use of higher frequencies, we do not think the existing applications are sufficiently close to those of wireless cameras to make the technologies relevant within the short term. We judge it unlikely that the use of 60 GHz frequency bands will be feasible in time for the London 2012 Olympic Games and Paralympic Games, though developments in these technologies should continue to be monitored.

Appendix A PMSE Frequency availabilities

The table below shows the existing allocation of spectrum for PMSE[10] together with bands which are to be auctioned and could, potentially, be used for PMSE. Other spectrum may also become available. The band from 2.39GHz to 2.69GHz, highlighted, is due to be partially cleared.

Start	End	Status	Notes
2.025	2.11	Current	Used on the basis of no interference to, and no-protection from, MoD Services operating in 2025-2070MHz. Airborne use permitted
2.20	2.29	Current	Used on the basis of no interference to, and no-protection from, MoD Services operating in 2200-2245MHz. Restrictions apply
2.39	2.69	Current	Available for Video Links. Some geographical restrictions apply. Some airborne use permitted, restrictions apply. The band 2500-2690MHz due to be cleared for award by Ofcom: PMSE licences may be revoked at 3 months' notice from 1 January 2007.
3.40	3.44	Current	Available for Video Links. Geographical restrictions apply.
3.50	3.58	Current	Available for Video Links. Geographical restrictions apply.
5.472	5.588	Current	Available for Video Links. Geographical restrictions apply.
5.68	5.70	Current	Available for Video Links. Geographical restrictions apply, Some airborne use permitted, restrictions apply
5.705	5.725	Current	Available for Video Links. Geographical restrictions apply.
5.73	5.75	Current	Available for Video Links. Geographical restrictions apply.
5.77	5.79	Current	Available for Video Links. Geographical restrictions apply. Some airborne use permitted, restrictions apply.
5.795	5.815	Current	Available for Video Links. Geographical restrictions apply. Some airborne use permitted, restrictions apply.
5.85	5.925	Current	Available for Video Links. Geographical restrictions apply. Some airborne use permitted, restrictions apply.
7.11	7.25	Current	Available for Video Links. Some geographical restrictions apply.
7.30	7.425	Current	Available for Video Links.
8.46	8.50	Current	Available for Video Links. Some geographical restrictions apply.

[10] UK Frequency Allocation Table FAT2007, Annex J

Start	End	Status	Notes
10.125	10.225	Auction	
10.30	10.36	Current	Available for Video Links. Geographical restrictions apply. Some airborne use permitted, restrictions apply.
10.475	10.575	Auction	
11.74	11.76	Current	Available for low power camera links.
11.81	11.83	Current	Available for low power camera links.
11.89	11.91	Current	Available for low power camera links.
11.97	11.99	Current	Available for low power camera links.
12.20	12.50	Current	Available for Video Links. Some power restrictions.
24.25	24.50	Current	Available for Video Links.
27.8285	28.4445	Auction	
28.8365	29.4525	Auction	
31.815	33.383	Auction	
40.50	43.50	Auction	
48.00	48.40	Current	Available for Video Links – until further notice by agreement with Ofcom

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