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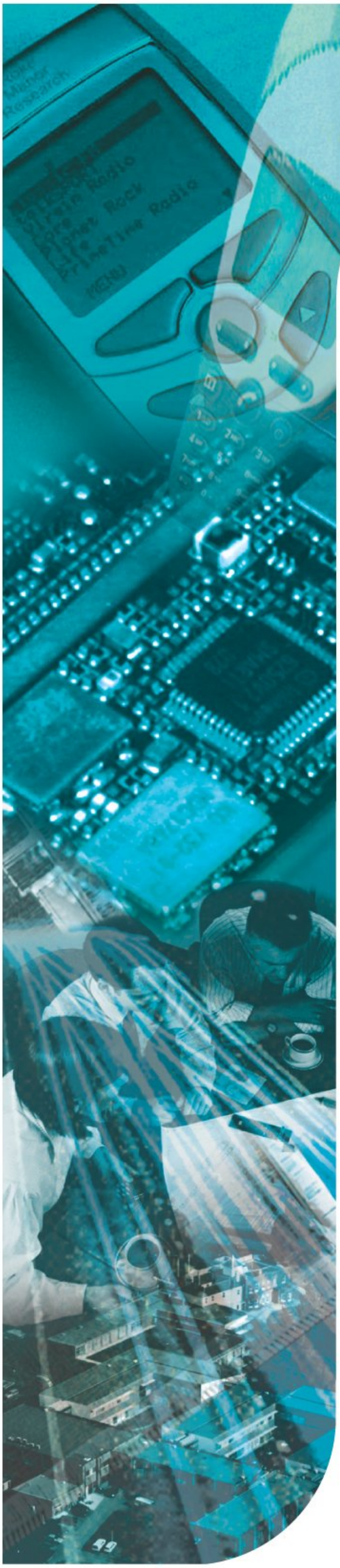

Review of Bandsharing Solutions - Final Report

Produced for: The Cave Independent Audit of Spectrum Holdings

Report No: 72/05/R/281/R
September 2005 - Issue 1
Against ITT: 1309

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SUMMARY

This report presents the results of a study for the CAVE Audit Team into bandsharing between radar and communications in the S-band (2.7-3.4 GHz). The primary radar user is air traffic control (ATC) but military and maritime radars also use this band. The motivation was to scope out the possibilities for bandsharing between communications and radar.

It was identified that a cellular communications system would be the best candidate for sharing with radar, giving high capacity and flexibility of service.

Several methods of bandsharing were identified and the two favourites: integrated sharing and spatial sharing extracted for further examination. Integrated sharing is a concept in which radar transmissions are used *as* downlink transmissions. Whilst initially appealing, further examination indicated that range disparities between radar and communications systems rendered this approach unworkable. On the other hand, these range disparities worked in favour of a spatial sharing approach in which communications cells were assigned frequencies that excluded those in use by neighbouring radars. This approach was therefore chosen for further study.

In order to facilitate and optimise a bandsharing approach it was necessary to improve the operation of the radars. Several known methods, including pulse compression, phased array and MIMO (multiple input/multiple output) radars were discussed. MIMO is very new but holds long term potential for significant advances.

It was felt important to highlight the requirement to develop both bandsharing systems jointly so that each satisfied its user requirements in the presence of interference from the other system.

Some consideration was given to the need for the communications system to operate in the presence of military and maritime radars. In particular, the concept of *ad hoc exclusion zones* was introduced to allow, for example, military exercises with a tactical radar to be performed in a given location.

In view of the safety critical nature of ATC radar, an examination of some new possible failure modes from bandsharing was performed. Possible mechanisms for mitigating these were identified.

Finally, consideration was given to the phases of a possible route to introducing a new bandsharing radar and communications future. It was concluded that the next phase should be a detailed feasibility study examining the link and interference budgets for a possible combined system concept.

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FIGURES

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1 INTRODUCTION

This document is the final output of a review of bandsharing solutions produced for the CAVE Audit Team in response to ITT 1309.

The initial scope of the work was quite broad, encompassing a wide range of frequencies and systems. During the course of the work, it was agreed with the audit team that this focus should be narrowed to consist of a study into concepts that could ultimately lead to successful wide scale sharing of the spectrum currently occupied by S-band radars, viz 2.7-3.4 GHz. The anticipated time frame for introduction of such a concept is of the order 10 to 20 years.

The structure of the report is as follows. Chapter 2 briefly presents the motivation and requirement for such sharing. Next, chapter 3 discusses, at high level, the kind of communications system that should be considered for sharing.

In chapter 4, a review of possible methods for bandsharing is given. Chapter 5 considers the two preferred options in more detail and proposes the better of these. It is considered that bandsharing will require some significant improvements to radar performance in terms of transmit power and receiver immunity to interference. Chapter 6 examines some relevant methods of obtaining these improvements.

Chapter 7 highlights the importance of designing the communications and radar systems *together* with joint optimisation of operation in the presence of mutual interference. Chapter discusses some of the practical issues involved in producing handsets suitable for operation in a bandsharing environment.

Although the main radar system for sharing is air traffic control (ATC), co-existence with military and maritime radars will also be required. Some pertinent issues are discussed in chapter 9.

In view of the safety critical nature of the primary user of spectrum, chapter 10 presents a brief consideration of new failure modes that could be introduced as a result of spectrum sharing along with some possible methods of mitigating these.

In chapter 11 a possible development route is presented at a high level. Finally, chapter 12 presents the overall conclusions.

2 THE REQUIREMENT/MOTIVATION

Spectrum for wireless communications has been at a premium for many years. This is not anticipated to change in the future. On the contrary, a study conducted by Analysys Mason [Ref 1] indicates that this trend is likely to continue over the next 20 years. Much of the spectrum at the lower end of the band to 15 GHz is well used and is unlikely to become available in the near future. The lower frequencies (up to about 4 GHz) are highly attractive because of their long range and non line-of-sight capabilities.

The S-band radars occupy a large block of spectrum that falls within the range of frequencies that are most appealing. These allocations were made at a time when spectrum efficiency was not a key driver, and so may not be the most effective use of this valuable spectrum. For radars it is difficult, exactly to define the measure of spectral efficiency. In a sense, such a measure is a moving target. However, given this a useful measure is the ratio of the spectrum currently in use to meet the requirements to that which *could* serve to meet those requirements if the most up-to-date technologies and concepts were applied. According to such a viewpoint, there is considerable scope for improvement in the use of these bands.

It is thus an aim of this study to identify means whereby all of the existing radio determination services provided through use of this band could continue to be provided if the band were shared with a new radio communications system.

3 THE COMMUNICATIONS SYSTEM

Here we consider the candidate type of communications system for sharing spectrum with the radar systems. Several such systems could be considered, for example:-

- Broadcast
- WLAN
- Broadband Wireless Access
- Radio Relay
- Cellular Mobile Radio

In reviewing the various possible systems for sharing we need to take a view on the needs and the possible economic benefits. Firstly, because the band is suitable (i.e. low enough in frequency) for mobile operation it would seem wasteful not to exploit this potential. Secondly, in view of the large coverage areas of radar and the large amounts of spectrum potentially available the promise is to be able to provide greater ranges than would be needed for WLAN operation. Conversely, interference considerations are likely to make the long range requirements of radio relay difficult to satisfy in a useful fashion.

For the above reasons it seems likely that some form of cellular communications system would be the best candidate for sharing with radar in the S-band. In fact, increasingly, cellular communications systems can satisfy a large number of service requirements, particularly if they are able to support high user data rates. For example, it is quite possible to have a common system providing mobile services and broadband fixed wireless access, as envisaged for WiMAX IEEE 802.16e.

4 POSSIBLE METHODS OF SHARING RADAR SPECTRUM WITH COMMUNICATIONS

There are a number of dimensions that can be employed, either singly or in combination, to support spectrum sharing. These include:-

1. Frequency division – It is a moot point whether this IS sharing in a strict sense but it is nevertheless a useful approach to consider where it is possible to reduce the spectral occupancy of an incumbent service to make room for a new provision.

2. Time Division – Here we consider a division of time between the two services. This can be on the micro level in which both services essentially co-exist but with very short term interleaving of the use of spectrum between the two services. Alternatively the sharing can be on the macro level in which the primary spectrum user (in this case the radar user) may relinquish the spectrum for alternative use at times when that primary user does not need it. Of these two options, clearly the former is preferable where possible because it allows continuous operation for the alternative user – i.e. the communications user. In the second case the sharing user is at the mercy of the whims of the primary user. It may be difficult to construct an economic case for investing large sums of money in such a concept. There could be an intermediate case where the sharing is possible with reasonable reliability at certain times of day (e.g. the night). However this is still much less attractive than continuous sharing.

3. Integrated Sharing – This is a radical solution in which a whole new infrastructure is constructed that meets the needs of both the radar and the communications services in a tightly coupled fashion. One such solution would be a concept in which the radar transmissions themselves were modulated with communications data. On the face of it, this is a highly attractive solution. This will be considered further in section 5.1.

4. Spatial Sharing - This is well known in cellular mobile communications systems. In such systems the terrain to be covered is divided into a number of cells. Every cell is served by a radio base station that facilitates communications to mobile terminals operating within that cell. The base station transmits information from the core network to the mobiles, providing downlink communications paths and receives information from the mobiles, forwarding it to the core network, providing uplink communications paths. Similarly, radar systems implement a measure of frequency re-use as indicated in [Ref 2] – section 3.2.1.4. One appealing approach is to establish sharing of spectrum between radar and communications on the basis of overlaid spectral re-use patterns, one for radar and one for communications in which the interactions between the systems are carefully managed.

5. Technology Managed Sharing – Here, the dimensions of previous sharing schemes can be extended through the use of highly sophisticated mechanisms. These include…

    a. Interference cancellation – For communications systems receiving interference from radars, considerable mitigation can be achieved through *a priori* knowledge of the radar transmit waveform characteristics, allowing local reconstruction and subtraction of the interference.

    b. Smart antennas – In both the radar and the communications systems significant improvements can be obtained, both in reducing interference generated and in reducing susceptibility to interference through the operation of smart antennas. In the case of radar, these antennas would take the form of phased arrays. One key element here is the tailoring of beam characteristics to minimise the generation/susceptibility to interference. Thus the generation of radar antenna patterns with extremely low side-lobes is of interest. In the case of smart antennas in communications systems, the current benefits are limited to the base stations rather than the mobile, the latter having obvious limitations in the practicality of multiple antenna element provision. However, some of the benefits of smart antennas in the base station impact on the mobile as well. Thus, for example, a base station antenna system that steers beams towards its mobile stations will provide increase antenna gain in the relevant direction, thereby reducing the power that needs to be transmitted by the mobile station.

    c. Dynamic channel selection. By monitoring the radio environment, either the communications system or the radar system[1] can dynamically select frequencies that are the most free of interference.

    d. Wide scale frequency hopping (FH). It is always possible to overlay a frequency hopping capability over a system. For the radar community this is well known in seeking to meet ECCM requirements [Ref 3]. In communications systems FH is a familiar method of randomising the source of interference and thereby improving spectrum as applied within GSM. In a spectrum sharing scenario this is particularly useful because it minimises the potential effect of a few unfortunately placed interferers.

In the next section we consider the more interesting sharing methods in more detail.

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[1] Or both but this could lead to tail chasing! In practice, it is most likely that the radar stations would remain fixed in frequency and the communications base stations and terminals would hunt for clear channels.

5 PREFERRED SHARING METHODS

5.1 INTEGRATED SHARING

According to this approach it is possible, in principle, to make the radar pulses include communications information. Specifically, the downlink spectrum of the communications base stations is used for radar transmissions. This is achieved by using some or all of the downlink communications transmission as radar transmissions. Possible antenna patterns in azimuth are shown in Figure 1.

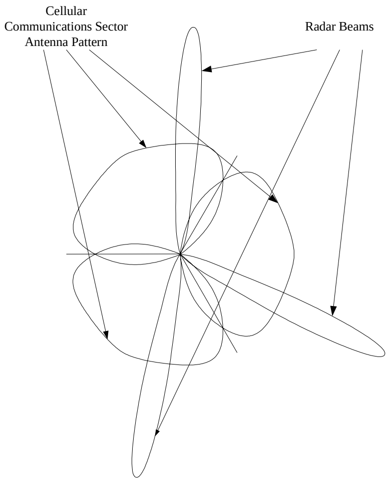

Figure 1 Azimuthal Antenna Patterns

Each sector antenna in the communications system provides independent communications to the covered sector. Each beam in the radar system is scanned across the sector to provide coverage of the applicable 120° sector. It will be appreciated that the use of three sectors is only by way of example. More or fewer sectors could equally well be considered. Indeed unsectored cells (360° coverage) could also be implemented.

Elevation patterns for a single sector are shown in Figure 2.

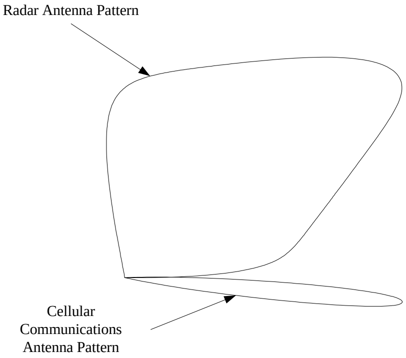

Figure 2 Antenna Patterns in Elevation

It will be noted that these patterns are substantially non intersecting. The communications down tilted sector is implemented very much as is currently normal for cellular communications. The radar antenna pattern in elevation is unusual for this application. It will be noted that it provides limited coverage at the horizon. This is to minimise interference to other communications cells. However, because the radar range requirements are modest for any given radar station it should still be possible to detect radar targets down to the minimum necessary altitude.

In order to operate with modest practical transmit powers the radar operating range should be the smallest that is practical and economical. The minimum required radar range capability is to reach an aircraft flying at maximum altitude (42,000ft or about 8 miles). Sensible coverage considerations suggest that the horizontal radar range could be made a comparable figure. Then the maximum (diagonal) required radar range would be about $8 \times 2^{1/2} = 11.25$ miles. The shape of the azimuth antenna pattern of Figure 1 is intended to reflect the requirement for increased gain at 45° elevation where the maximum range is greatest. The round trip delay corresponding to 11.25 miles is about 120 μs. The transmission period will be based on this (or the round trip delay computed from any other selected range). Thus, for example, transmissions can be made with 120 μs duration. It will be appreciated that all radar returns of these transmissions except those from targets at maximum range will be at least partially overlapped with the transmission – i.e. the transmission will overlap the reception. However, conversely, there will always be a part of the radar return that is *not* overlapped with the transmission. Thus, if the 120 μs transmission is followed by a 120 μs transmission *gap* the available returns can be detected.

The principle, then, for each return is to correlate only that portion of the return that is visible *after* the end of the transmission (allowing that there will be some loss of visibility for minimum delay returns due to the transmit to receive switching time). In practice there will be some difficulties due to the very wide dynamic range of returns. The earliest returns will be much stronger than the later ones and the processing gain due to correlation against the transmitted communications signal will be inadequate to avoid breakthrough from the short range returns to the long range measurement cells. This difficulty can be partly resolved by performing only partial correlations of the later part of the bursts so that very strong components of earlier returns are either not included or only partially included in the correlations.

However, for the earliest returns, on one hand, the period for correlation is too short to obtain significant processing gain and on the other hand the dynamic range is very large. These requirements cannot, therefore be satisfied by the communications transmission. For this reason it is necessary to incorporate a single pulse transmission, prefacing the coded transmission with a suitable gap for reception.

The pulse structure is shown in Figure 3.

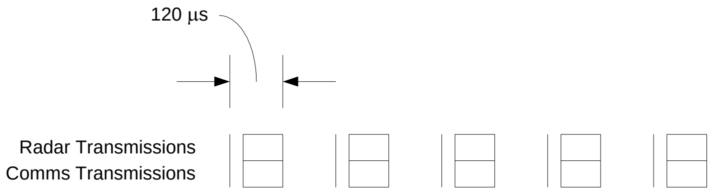

Figure 3 Basic Sharing of Radar and Communications

The signal in the radar and communications transmission is identical. The only difference is that the communications signal is radiated through the sector antenna whilst the radar signal is radiated through the elevated beam.

Normally FM radar operates allowing reception of returns *during* the transmission of the extended duration pulse. However, typically this relies on the following considerations:-

1. The pulses are typically constant envelope[2]. This makes cancellation of the leakage signal much more straightforward

2. Often separate antennas are used for transmit and receive, providing increased attenuation for the leakage path. If phased array antennas are used this is not very attractive.

It is not essential for the gap in transmission to be quite as long as the period of transmission. However, to the extent that it is shorter, there will be a loss of sensitivity and therefore, of range. It would also be possible to make the radar transmission pulse shorter than the communications burst whilst using the same modulation for the radar pulse that is being used for the corresponding part of the communications burst. However, if this were done there would be a

---

[2] i.e. the signal amplitude is unmodulated over the period of the extended duration pulse

discontinuity in phase and amplitude in the signal as received at the mobile station arising at the time when the radar signal is activated. It would be possible to mitigate this effect by incorporating separate channel estimation reference data in the two parts of the burst. This reference data could take the form, for example, of ‘ambles’ (pre, post or mid) or periodically transmitted pilot symbols. The communications receiver in the mobile station can then capture the first (radar free) part of the burst and the second (radar present) part of the burst (either separately or as part of a single capture process) in the form of digitised complex base band. Independent channel estimates can then be formed from the separate reference data in the two parts of the burst and used separately to demodulate the two parts. There is no point in making the radar burst component any longer than the transmission gap.

One possible example of this operation is shown in Figure 4.

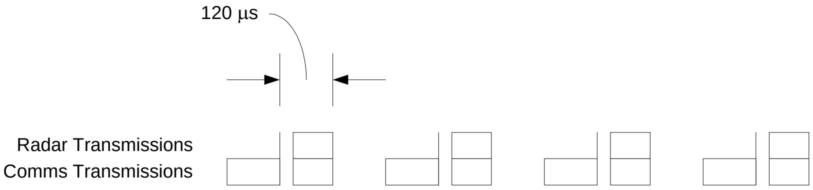

Figure 4 Radar and Communications Sharing with Extended Communications Burst

In this case the communications transmission is roughly twice as long as the radar transmission. However, both parts contain training data to allow independent channel estimation.

In general the combined radar and communications transmissions followed by transmission gaps need not appear on a regular basis. It would rather be possible to incorporate them according to some form of pseudo random pattern such as that shown in Figure 5.

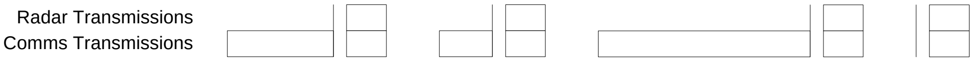

Figure 5 Pseudo Random Transmission Pattern

This approach allows ambiguity resolution over target doppler shifts whilst also, in general, reducing the overhead associated with the radar operation. In multiple doppler filters the returns corresponding to the same delay from each of several radar transmissions can be summed after multiplying each received complex sample by the phasor having a phase shift derived from doppler shift of interest and the (possibly non uniform) transmission delay associated with each sample.

Alternatively, a variety of fixed transmission rates can be cycled through as illustrated in Figure 6.

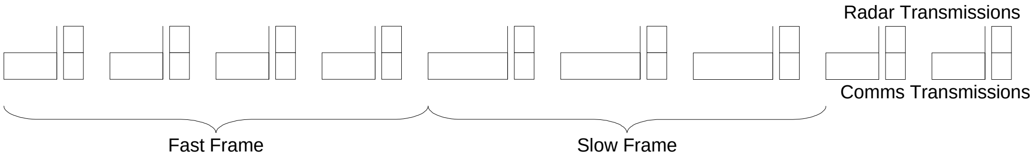

Figure 6 Twin Frame Transmission Pattern

A further alternative is to toggle between two duration or more transmission durations in a regular pattern as illustrated in Figure 7.

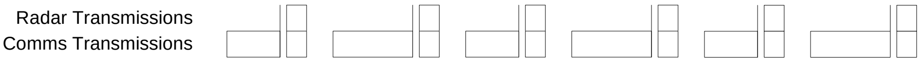

Figure 7 Toggling Duration Transmission Pattern

If the radar component of the sharing scheme is to provide adequate functionality to support at least some of the military requirements it will need to be able to measure the elevation of targets as well as the slant range and azimuth angle. This can be achieved through the use of crossed arrays in which the vertical array stares at the targets identified by the horizontal array in order to determine their elevation. This will allow both the identification of low level fast moving targets *and* reliable handover between radars to provide a composite picture.

Although novel, and having some useful features there are several problems with the above approach:-

The crucial issue is power disparity. It is intellectually appealing to have transmitters that serve the needs of radar and communications simultaneously. However, the powers needed for radar are much higher than those needed for communications. In the above description it has been attempted to reduce this disparity somewhat artificially by reducing the range requirements of the radars. This does not fit naturally with the operation requirements of radar, specifically:-

1. ATC Radars need range out to sea of at least 60 NM.
2. Air defence radars need range to high altitudes with low RCS targets.
3. Military radars need to track aircraft flying at low altitude with high speed. This could lead to a high handover rate for short range radars, leading to greater potential for track miss-alignment

Even ignoring these effects, it is likely that the communications system will frequently require micro-cells to meet the requirements. Moreover, modern communications concept increasingly lead to tighter frequency re-use. For example, CDMA as used in 3G re-uses the same spectrum in *every* cell, and increasing use of smart antennas will allow frequencies to be re-used at least once per cell site. Given this, in the above concept there would be cells using the same frequency as the radar operating very close to it.

Thus the above concept could really only fully be used in the case where the radio communications range was comparable with the radar range. In reality this would not applicable to cellular communications as the terminal powers would be far too large, particularly for broadband applications.

5.2 SPATIAL SHARING

In a normal cellular mobile radio system, re-use is facilitated by dividing the available spectrum into sub portions, usually according to an FDMA structure. The number of such sub portions is equal to the so-called cluster size of the re-use pattern. Nominally the re-use pattern consists of a number of tessellating re-use clusters, each consisting of a number, equal to the cluster size, of tessellating, hexagonally shaped cells. The base station serving each cell in a given cluster is assigned a different sub portion of the available spectrum. In this way the distance of a receiver to the nearest interfering transmitter, whether uplink or downlink using the same spectrum sub portion is increased according to the cluster size.

Some radar systems also can operate according to a spatial re-use structure in which contiguous or partially contiguous radar radiolocation coverage of a large area can be provided by a number of smaller overlapped radar coverage areas, each served by a single radar, wherein, again, a pattern of radar usage frequencies is assigned to the radars to reduce interference from interfering radars by increasing the range to the nearest radar using the same frequency.

Here we consider a method for providing such combined radar/communications spatial re-use pattern. One example is illustrated in Figure 8.

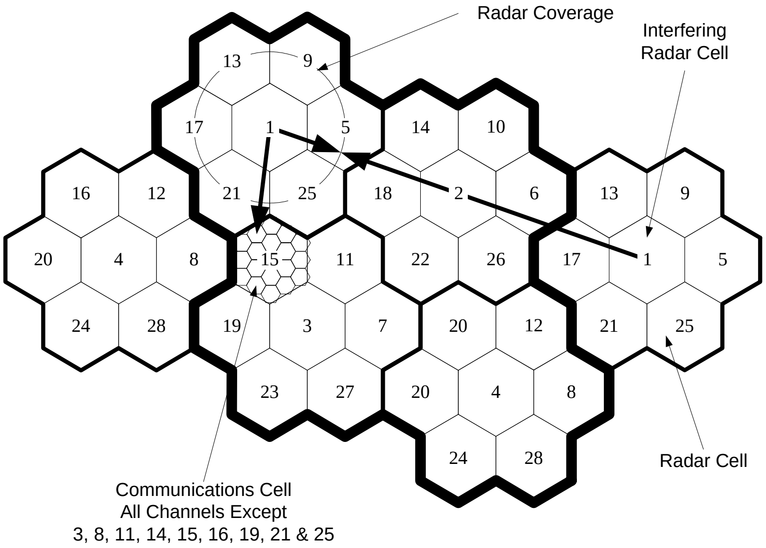

Figure 8 Spectrum Sharing Spatial Re-Use Pattern

The figure shows a number of radar cells illustrated as larger hexagons, each containing a number. Each radar cell contains a radar transmitter at its centre and the frequency of operation of the radar transmitter is denoted by the number contained in the cell.

It can be seen that, in this simple example, the re-use cluster size for the radar pattern is 28. The cluster pattern is denoted by the cells contained within the heavy outline. It can also be seen that this pattern provides considerable separation between radars using the same radio channel, as highlighted by the arrows related to two radar cells both using radio channel 1. Moreover, it can be observed that none of the radar cells has any neighbours that use its adjacent channel – i.e. there are no neighbouring cells whose numbers are separated by only 1.

The radar cells are typically large (tens of miles). On the other hand cells for radio communications can be very small. This reflects the following requirements:-

1. Terminal transmit powers are limited by battery power/life and safety considerations.

2. Increasingly high bit rate requirements degrade inherent receiver sensitivity, reducing path loss capability.

3. Requirements for high capacity, supporting large numbers of users. Since any given cell supports a fixed number of users, shrinking cell sizes increases the density of users that can be supported.

We consider a cellular system that must operate using spectrum shared with the radar system. Such a system might operate using any of the known cellular mobile radio multiple access schemes such as FDMA, time division multiple access (TDMA), code division multiple access (CDMA), orthogonal frequency division multiplex (OFDM) or orthogonal frequency division multiple access (OFDMA). These technologies have increasingly permitted smaller re-use clusters, thereby improving spectrum efficiency.

The principle relates to a cellular radio communications system whose cells are small enough that, in general, many are contained within a radar cell. We determine the frequencies that are available for sharing by the cells of a radio communications system on the basis of the radar cell that contains those radio communications cells. Thus we make all of the radar frequencies available for sharing apart from a subset that are excluded, dependent upon the radar cell that contains the radio communications cells. The most basic exclusion is to exclude the frequency that is used by the radar operating in the radar cell. Depending upon the relative wanted and interference path losses, additional exclusions may also be considered, i.e.

1. Exclude the adjacent channels of the radar operating in the radar cell

2. Exclude the alternate channels of the radar operating in the radar cell

3. Exclude the channels in use by the radars operating in the cells surrounding the radar cell. This could be extended as necessary to further rings around the radar cell of interest.

4. For sectored radio communications cells, exclude the channels in use by those radars operating the cells surrounding the radar cell that fall substantially within the sector.

For a sensible size radar re-use pattern, such considerations can lead to a high efficiency of sharing with communications. For example, consider Figure 8 again. In this case consider exclusion of the containing radar frequency and exclusions 1 and 3 above. This is illustrated for the cell having a radar operating on channel 15. It is shown that channels 3, 8, 11, 14, 15, 16, 19, 21 and 25 must be excluded out of a total of 28 available channels. This would leave 19 cells available for re-use, i.e. about 68% of frequencies.

In a more realistic scenario there might be 49 frequencies, in which case excluding the applicable 9 frequencies for every cell would lead to about 82% efficiency of re-use.

Note that this number of frequencies, used in conjunction with a modern cellular communications technology will very likely support the use of multiple, possibly even all available (i.e. the subset of frequencies available through bandsharing), frequencies at any given cell site.

The type of spatial re-use scenario described above will need to be analysed in considerable detail to determine its viability and operational parameters. From the viewpoint of the communications system, the following considerations are important:-

- The communications cells are likely to be short range. Indeed, satisfaction of high user demand dictates small cells. Where this level of demand does not exist (e.g. in rural areas) it is unlikely that the system would be deployed. For modest demand increases it could be less expensive, slightly to increase the infrastructure density of an existing system (such as 3G or WiMAX) than to deploy this new type of system.

  In regions where sharing is not required it might not be necessary to replace the existing radars. However, it is likely that there would need to be, at very least, a boundary overlap of modified radars such that some of the modified radars would extend into the region of non use. This would be necessary to maintain the re-use pattern. Very detailed planning on a case-by-case basis would be needed to guarantee safety of operation whilst minimising the overall costs.

- Short range cells will mean relatively low base station antennas that fall below the path of the radar signals at the kind of interference ranges envisaged. Also, short range operation will lead to comparatively low transmit powers in both (uplink and downlink) directions.

- Base stations will typically have down tilted antennas to improve capacity within the communications system. This will also have the effect of reducing interference to/from the radar stations.

- In the time frame under consideration (10-20 years), the use of smart antenna technology for communications is expected to become commonplace wherever high capacity is desired. As has previously been mentioned, this will allow transmit powers to be reduced further.

- Frequency hopping has been mentioned in relation to radar spectrum sharing. This technology is a useful component in cellular communications systems. It is an option in WiMAX[3]. If FH were applied to the communications spectrum, permuting around the available radar-shared carriers with time switching parameters selected to randomise interference to radar then further gains would be possible.

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[3] Although implemented as form a permuting of the sub-carriers within an OFDM mix

5.3 SPECTRUM SHARING CLOSE TO A RADAR SITE

In a spatial sharing scenario such as that described in section 5.2, the very closest cells to the radar might experience interference from the radar because of the very high powers involved even if the actual radar frequency is not used. This effect will be somewhat mitigated by the fact that there should be no users operating inside the high intensity radio transmission area (HIRTA).

One possible method of solving this problem could be to use the integrated sharing solution of section 5.1 *but only for that cell*. In this case there will be no interference to the other cells because they will be using entirely different frequencies. This approach has unfortunate aspects, however. Firstly, it will work only for the downlink. Separate spectrum will be needed for the uplink. Secondly, it introduces constraints on the design, and therefore performance, of the radar that would otherwise not be needed. The gain in terms of service – communications function over one small cell per radar station – would not seem to justify the costs implied.

A simpler solution would be to arrange coverage by having the radio communications base stations offset from the radar station's location and using radio frequencies with as large as possible a distance in MHz from the radio frequency of the radar station.

6 METHODS OF IMPROVING RADAR PERFORMANCE

The spatial sharing scheme of section 5.2 is the preferred approach to bandsharing. However, some significant improvements will be needed to the radar performance to make this concept viable. The radar spatial re-use operation will require good spectral containment of the radar pulses in order to achieve the channelisation necessary to avoid out-of-channel interference. It will not be possible to meet these requirements with Magnetron radars. Other issues are as follows:-

1. *Use of pulse compression radar* – Many existing radars transmit simple band-limited impulses. These have a high peak to mean ratio, therefore requiring high peak powers. In addition the scanning antennas also have high gains so that the peak effective power emitted in the scanned direction (EIRP) can be extremely high, generating large amounts of interference and placing limitations on the technology that can be used to generate the RF. Considerable benefits can be obtained by using pulse compression radar [Ref 2] - section 3.2.5.9. Here the transmissions are made for a period significantly longer than a pulse (by a factor of the 'time-bandwidth' product). In the receiver, correlation is performed over this period to recover all of the energy and the distance resolution. The coded waveform based on communications data described in section 5.1 is a specialised version of this type of radar. Improvements of 15 – 25 dB can be obtained by using pulse compression radar.

   A further potential advantage of pulse compression radar is that, provided potentially interfering radars use different waveforms, there will be considerable discrimination against that interference.

2. *Phased array technology* – In a phased array all of the RF power that must be generated is scattered over all of the array elements and therefore the power per element is significantly reduced. This aids considerably in achieving an all solid-state design that will have improved spectral characteristics.

3. *MIMO (Multiple Input/Multiple Output) Radar* – This is a new technology for radar that holds substantial promise for the future [Ref 4]. In a conventional radar the transmit beam can point in only one direction at a time. Even in a sophisticated phased array radar the number of parallel beams that can be transmitted is limited to a small number. In a MIMO radar, essentially all beams are transmitted in all directions at once. The principle is that every element transmits a unique waveform that is, to a large degree, independent of the waveforms transmitted by every other element. In the receive phase of the radar, by correlating against each of these waveforms, in the output of every receive element, the radar receiver can separate out the signal from every transmit element in every receive element. By combining these in suitable ways the receiver can re-construct the received signal as though receiving every possible transmit beam.

This has two advantages. Firstly, there is no *actual* transmit antenna gain as seen by any external receiver. This means that peak interference is considerably reduced. Note that this gain is *in addition* to any gain from pulse compression[4]. Secondly, it is possible to have the radar stare in as many directions as desired for as long as necessary. This means that the radar receiver can correlate over longer periods of time than a conventional radar, improving sensitivity and permitting yet further reductions in transmit power.

MIMO radar is currently very much in its infancy. Its widespread take up will require technological advances and cost reductions. Once the all-digital[5] phased array becomes commonplace, the MIMO processing may be expected to follow on naturally. The number of directions that can be 'stared' at in parallel will grow with processing capability. This will increase substantially according to Moore's Law. Because the processing itself is highly parallel, it will not matter if Moore's Law follows a similar (i.e. parallel) growth pattern in future.

The above improvements in radar performance will require considerable investment. Some of this will come in the military since many of the developments will lead to operational advantages. Others could come from some form of 'crossover' investment where capital is made available from supporters of the communications system venture to make it possible for the radar community to share their spectrum more effectively.

7 JOINT DESIGN CONSIDERATIONS

When sharing of spectrum between different types of user is mooted, an inevitable question is "What degree of interference between the two systems is permissible?". For example, by how much should we allow the noise floor to be raised in the victim receivers? – particularly in any safety critical system. When a new system is introduced into an existing band with incumbent safety critical users these are entirely reasonable questions to ask. However, when we consider the joint design of two systems that are intended to share spectrum *from the outset*, a different approach is appropriate.

In this case, both sharing systems should be designed to meet their service requirements *in the presence of the anticipated/designed interference levels from the other system*. Thus, for example, it is of no consequence whatsoever, if such a radar regularly experiences a 3 dB rise in its noise floor due to interference from spectrum sharing communications elements, provided it was designed to satisfy its performance criteria in the face of such interference. This is likely to mean that the power budget for the radars will need some additional margin. However, two key mechanisms for reducing the transmit power have been identified in section 6 and these will more than offset any power increase needed to satisfy this requirement.

Of course, any increase in radar transmit power will lead to an increase in interference *to* the spectrum sharing communications system. However, even if this led to an increase in the transmit powers for the communications system there is still a net overall capacity benefit in operating *above* the noise floor. This is because the fundamental or 'pole' capacity of any radio system occurs when it is *interference* rather than noise limited.

8 PRACTICALITIES OF COMMUNICATION EQUIPMENT

Any communications system designed to be operated in spectrum shared with radar will inevitably have a higher complexity in its equipments. For a cellular system the critical area will be in the terminal, particularly if these take the form of handsets, so we focus on these.

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[4] In fact the use of the codes to separate out the individual transmit elements in a MIMO radar means that a MIMO radar is almost always a pulse compression radar.

[5] In this case 'all-digital' means that the baseband waveform for every element is synthesised digitally and the received waveform is also digitised to baseband. It is not intended to imply that the final RF signal is generated all digitally.

If bandsharing is accomplished by means of spatial re-use then downlink sharing will be achieved through antenna design at the base stations. In particular, the use of antenna down tilt should significantly reduce propagation to distant radar sites. In addition, other modern techniques such as space-time diversity and adaptive coding and modulation may be employed to improve the link budget in the downlink direction, allowing the required range to be achieved with reduced base station transmitted power. These techniques are already practical for implementation in handsets.

In considering the uplink, there is more concern because, in general, the mobile antenna pattern and location is uncontrolled. Handsets can be used in high rise buildings where large visibility is possible. The problem in this case would be somewhat mitigated by the operation of power control which would significantly reduce the transmit power provided there was a line of sight path to the base station.

There are several techniques that can be applied to solve or mitigate these problems:-

- *Use a separate (i.e. non bandshared) band for the uplink* – This approach would be based on the premise of asymmetry of data transmission requirements in the two directions so that it is easier to find a band suitable for the relatively small uplink needs.
- *Selectively use alternative band for uplink* – The concept here is to use bandshared spectrum for most uplinks but where it is identified that a mobile link could generate significant interference at long distance, use an alternative band. The vast majority of links would thus use bandshared spectrum so only a relatively narrow alternative band would be needed. The technical challenge here is clearly to detect the possibility of generating excessive interference. One method would be to use GPS and terrain data to detect the height of the mobile above ground and use this to determine the selection.
- *Apply fade mitigation technology* – There are several techniques that can improve the link budget for the uplink involving the use of more than one antenna element in the handset. Opinions vary within the industry on the practicality of this, although several highly respected industry authorities (e.g. Jack Winters, ex AT&T) believe it will happen. This would allow reduced transmit power, thereby mitigating possible interference.

In summary, it is believed that, although some increase in complexity will be required in terminals to facilitate bandsharing with radar, this rise will not be excessive but will be in line with the general technology trends within the industry.

9 ISSUES OF CO-EXISTENCE

The band of interest provides ATC primary radar functionality. Sharing spectrum with this service should be relatively straightforward given all of the tools available. However, the military and maritime communities also use this spectrum and their requirements must be satisfied.

9.1 MILITARY RADAR

The military use several different categories of radar including air defence and tactical. In addition some of the radars in use implement ECCM techniques such as frequency hopping. The range requirements for military airfield radar can extend out to 120 NM and further may be needed for air defence although this range requirement should not apply inland.

Many existing military radar are quite profligate in their use of spectrum, particularly those that achieve scanning in elevation through frequency sweeping. These have a number of horns with different tuned frequency of operation connected together and fixed at different elevation angles. As the signal frequency is swept, so the preferred horn changes, thereby altering the angle of elevation.

Looking into the future, essentially we need to distinguish between those things that can and can't be changed. Clearly we must continue to meet our obligations under NATO. On the other hand, it should be possible to replace some radars with new designs that meet their requirements (including foreseeable needs for improvement) with reduced spectrum occupancy.

Taking a more generic view of military radar, the issues that are non negotiable and likely to remain so are:-

- *Long range operation* – This is not a problem in principle. The concept of section 5.2 already supports the deployment of relatively long range civil ATC radars. If most of the long range operation is constrained to seaward directions then interference effects should be acceptable.

- *Ad hoc rapid deployment* – The issue here is the possibility of a radar being deployed at any location at short notice and possible deleterious effects of interference to/from the communications system. A possible solution to this problem is described later in section 9.2.

- *Use of ECCM Radars* – Radars designed to resist the threat of jamming or other exploitation techniques may make wide and unpredictable use of the spectrum within the band. One possible technique is frequency hopping. Considering interference *to* the radars, it can be appreciated that this interference is a form of *friendly jamming*. As such, any ECCM radar worth its salt should be able to operate without difficulty. Considering the re-use patterns of Figure 8, there will always be a number of uninterfered frequencies around every possible radar location. An ECCM radar should be able to exploit these frequencies to provide the necessary service.

  In the case of interference *from* the radar to the communications system there are many potential solutions. However, the degree to which these solutions could be implemented would depend on the amount of information that could be made available to the communications system design authority. A compromise will probably be needed here since, on one hand there is a need to meet security requirements (i.e. to avoid risking loss of some of the anti jamming advantage), on the other hand it is still highly desirable to facilitate satisfactorily co-existing communications. One possible route would be to arrange for closed session collaboration between the military radar community and selected communications system designers to develop radio parameters and techniques that *will* allow the communications system to operate successfully in the presence of the relevant ECCM radars. The goal would be to specify these design elements *without* identifying the exact reason for their value/characteristics and in such a way that it would be extremely difficulty to infer anything useful about the radar from them. This would obviously be a sensitive task.

9.2 AD HOC EXCLUSION ZONES

It may be necessary at times to permit the operation of uncontrolled military radars, outside the re-use pattern of radar stations. When this happens, mutual interference between the communications system and those uncontrolled radars may need to be mitigated. One approach to this is to provide a facility for introducing *ad hoc exclusion zones*. The mechanism for implementing this functionality would require a communications infrastructure over a core network with the following features.

1. The uncontrolled radar knows the frequencies it desires to operate.

2. There is a pre-agreed or, determined by measurement, minimum distance from radio communications cells using the same frequency as the uncontrolled radar.

3. Base stations within the exclusion zone defined by '2' are informed that they can not use the designated frequency(s) by addressed signalling over the core network.

4. The radio communications system continues operating without the designated frequency(s) until informed by another signal over the core network that they can now operate using the previously designated frequency.

It would also be desirable to arrange, as appropriate to re-plan any cellular re-use pattern for the communications system to avoid loss of coverage and/or to make capacity (albeit reduced) more uniform.

Inevitably, whenever such a temporary exclusion zone is implemented there will be some reduction in service for the communications system. The significance of this will depend on several factors:-

- *The location of the reduction of service* – To some degree, however, this is self balancing, i.e. it will be those areas that have implemented the highest density (and therefore capacity) system that have most to lose. On the other hand, the densest deployments of communications infrastructure will have the shortest range paths and may therefore be more likely to operate successfully without unacceptable interference to/from the uncontrolled radar. If/where there are regions where loss of throughput is critical it may be necessary to over provision capacity (e.g. by denser infrastructure) so that temporary loss of spectrum (and therefore throughput) can be accommodated whilst still satisfying the service requirements.

- *The time of day when service is lost* – Clearly if the uncontrolled radar needs to operate continuously for a period of a day or more then this issue becomes irrelevant. On the other hand, if it is possible, for example, to schedule radar training sessions to take place outside normal working hours then the loss of service might be acceptable without difficulty. Exploiting such diurnal variations would require an ad hoc exclusion zone capability that could perform rapid time based switching. One method could be to arrange the exclusion zone controller to send a *diary* of frequency assignment changes to the relevant base stations. In this case the changes could be implemented with high flexibility.

If the bandshared spectrum is used to *enhance* the throughput of existing services then when there is a reduction or even a loss of this enhancement, the existing service will remain.

9.3 MARITIME RADAR

Maritime radars also operate within the band of interest. The radars typically use short pulse transmissions with wide bandwidths. Considering immunity of the communications system to interference *from* maritime radars, much can be achieved through appropriate design of both the standard and the equipment (in particular the receivers). For example, use of frequency hopping would randomise the location of the interfering radar in such a way that nearby radars interfere only infrequently. In the receiver, circuits can detect short duration, high amplitude pulses and excise these from the wanted signal. All modern communications systems use forward error correction (FEC) coding and the proposed system will be no exception. Moreover, modern receivers implement ‘soft’ decision decoding wherein the operation of the error correction decoder is enhanced by exploiting reliability information associated with the received data. Where it is known that interference has affected a particular received data bit this can have its reliability metric set to zero, thus declaring that bit to be an erasure in the decoder. This side-information can be particularly useful in combatting the effects of pulsed interference.

The effects of interference from the communications *to* maritime radars can also be minimised by a number of techniques. As stated earlier, the use of short range cells reduces the required transmit powers and therefore the interference levels. In considering coastal interference we have the option of constraining base station antenna patterns to avoid transmitting out to sea. This will be possible with sectored cells where there is no sector operating in the seaward direction. In some cases, given the fractal nature of the coastline, this may require an increased number of base stations. However, it must be kept in mind that the purpose of this new communications system is to provide a quantum increase in capacity *where that is needed*. In many parts of the country, coastal regions are also rural so that the new system might not even be deployed in those locations. On the other hand the bandwidth provided by the new communications system may be of considerable interest around major ports and docklands. Provision in such locations will need to be supplied with care. One option would be to deploy micro-cells where transmit powers could be kept low. An alternative could be to place a thin *final layer* of 3G micro-base station in such locations nearest to the sea so that capacity could be provided *without* generating interference out to sea. Of course such a solution would require inter-system handoff capabilities between 3G and the new communications system. However, previous generation handoff has become a given in the cellular communications industry.

It will also be necessary for the communications system to operate in the presence of radars operating within inland waterways. However, here the range requirements of the radar are significantly reduced compared with sea requirements so it should be possible to cope with such interference using the techniques that have already been described. Land based inland S-band radars can operate with reduced power whilst ship radars could use X-band that provides better resolution.

10 FAILURE MECHANISMS

For any safety critical system subject to interference from a band sharing system, it is crucial to ensure that failure modes in the sharing system cannot create interference in the safety critical system that compromises its operation.

In the case of a communications system sharing spectrum with a radar system the main failure mechanisms that could impact on operations are:-

1. Base station transmit at excessive power;
2. Base station transmit on incorrect frequency;
3. Mobile station transmit at excessive power;
4. Mobile station transmit on incorrect frequency.

In addition with smart antennas it is conceivable that a failure mode might cause a base station to generate a high gain transmit beam towards a radar (also given that it transmitting on an incorrect frequency). This is, however, highly unlikely.

For each of the above cases, failure mode detection can be implemented to switch off any equipment that is behaving inappropriately. The issue will then be the impact of the interference caused between the appearance of the failure and its detection and removal (assuming that the detection and removal is successful).

For the base station it may be necessary to incorporate an independent method of measuring the transmit frequency (e.g. a counter). Incorrect values would trigger a de-activation and flag a failure over the network. The mobile’s transmit frequency could have a fixed relationship to its receive frequency. Transmission should be inhibited unless the mobile is receiving a signal from the base station. Transmission could be further inhibited if the mobile fails to receive a response to its transmission from the base station within a timeout period.

A more flexible approach would be for the mobile to be given information specify exclusion bands in which it is not allowed to transmit. This would allow intelligent use of spectrum whilst guaranteeing protection of the radar systems.

It is anticipated that both for reasons of sharing and capacity, automatic control of transmitted power would be implemented in both directions. The maximum transmit power for any given terminal/base station channel should be designed to meet the worst case path loss conditions. The peak total transmit power from the base station should be set to be slightly higher than that needed to meet the average requirements over the cell that it serves. If a single mobile fails in such a way that it always transmits at maximum power, the impact on the average power in the channel should be modest. Equally, if the base station transmits at its overall composite maximum power the power rise should not be great.

It may be appropriate to include a further level of inter-system control of interference. Thus a radar station could detect interference. If there were some mechanism whereby the radar receiver could identify the signature of a particular cell (whether the base station or mobiles within that cell) as a source of unacceptable interference it could signal via the core network to that cell to disable it. This would need further investigation.

It should be noted that 100% overlapped radar coverage would provide redundancy against *all* possible failure modes *including interference*. Thus, if a radar experiences interference from a communications transmission it is likely that an adjacent radar, using a different frequency and with a different spatial relationship to the source of interference will not.

11 DEVELOPMENT AND TESTING

The existing ATC radars operating in S-band are safety critical. Any changes to their operation and/or interference environment must be vigorously tested to demonstrate that the safety requirements can be completely satisfied. The introduction of the new concept would require parallel design and development of the radars and communications system. This would be an unprecedented venture, requiring the bringing together of radar and communication experts in a fully collaborative environment. Such facilities as Roke Manor Research Limited would be well placed to begin such a process, already having both skill sets working together in a single business unit. It is possible that the scale of development required could lead to a new industry built around the integrated skill sets.

The further development of the concept would include the following phases:-

1. *Detailed feasibility, link/interference budgets* – This would require detailed propagation modelling for both the wanted and the interference paths and analysis of radar and communications requirements. The purpose of such a study would be to scope the system concepts in terms of cell sizes, throughput, transmit powers, radar ranges and scan rates to an initial order of magnitude.

2. *Radar and Interference Trials* – Using radars representative, in terms of appropriate parameters, of those ultimately to be developed, assess the level of interference to/from locations at various ranges, powers and bandwidths. To some degree this would provide a check on the results from the previous phase, confirming the viability of the proposed solution.

3. *Refinement of Concept, Development of Standard and Simulations* – It is likely that, at this stage the process would move into a public standards forum. Whether or not this is international (e.g. ETSI) would depend on the results of a parallel process of ‘selling’ the concept (at least) within Europe. Of course, the UK could pursue this course alone. The implication of this would be a potentially smaller manufacturer base to amortise development costs. In addition, trials would be needed to ensure that no unacceptable interference was generated/received to/from mainland Europe. The standardisation process would be unique in that it would be the first time that the waveforms and operation of a radar equipment were standardised. In addition it would be necessary to specify receiver as well as transmitter performance in order to guarantee immunity to interference and to ensure that both (radar and communications) systems can operate at the minimum transmit powers. The running of detailed simulations at this stage will be crucial in obtaining in-depth understanding of the operation of the communications and the radar systems, operating both independently and together.

4. *Safety trials* – An issued public standard is an invitation for manufacturers to produce equipment according to that standard. Because of this, any standards produced in phase 3 would need to be kept at a pre-issue state until comprehensive safety trials had been completed and any necessary iterations performed to obtain a viable (i.e. safe) design. Paying for the development of trials equipment and the conduct of the trials is likely to require some industry wide collaboration to share out the costs and risks.

   One difficulty with these trials will be avoiding causing interference to the existing ATC system. Although it could be possible to design the trials equipment to operate in another band, by definition, there is little spectrum available for this and if the band is too far displaced in frequency the results will not be representative. It is therefore likely that a combination of very careful frequency planning and choice of trials region will be needed to facilitate the trials. It might even be necessary to conduct some of the trials at night.

5. *Full Development, Production and Deployment* – Once the standard has been issued following iterations it should be possible for manufacturers to develop and manufacture equipment accordingly. A phased handover from the previous radars to the new will be required. It is possible that the new radars will need to

use the same frequencies as the those used by the ones they replace until the whole (or most of the) replacement programme is complete. Equally, it is likely that the radar replacement would need to be complete before any communications infrastructure could be activated. Activation of the communications system should be performed in a phased fashion where the impact of interference at the radars can be assessed according to known activations.

12 CONCLUSIONS

This report has presented a number of methods for sharing spectrum between ATC radar and a new wireless communications system in the S-band in the 10-20 year frame. Two approaches for bandsharing: integrated sharing and spatial sharing have been considered. The preferred approach is based on spatial sharing of spectrum between the two systems, wherein the distance between users of the same spectrum in the two systems is maximised. Initial estimates suggest that well over 50% of the radar spectrum should be available for sharing although a detailed study will be required to verify this.

In order to facilitate and optimise this sharing scheme, it will be necessary to improve the performance of the radar stations. In particular, it will be highly desirable to reduce the transmit power for a given range as well as improving the immunity to interference. Several known methods for doing this have been identified, including the use of pulse compression, phased array technology and MIMO.

The need to develop the new radar and communications systems jointly has been highlighted. In particular, any anticipated de-sensitisation of the radar by communications generated interference must be factored into the radar link budget from the start.

Issues around bandsharing with military and maritime radars have been considered. The desirability of designing the communications system to generate ad-hoc exclusions zones at will has been identified.

Because of the safety critical nature of ATC radar, a brief examination of failure mechanisms that could impact the radar performance has been considered. Some failure modes have been considered and possible solutions identified.

The parallel generation of two new systems to share spectrum, particularly where one is safety critical, represents a unique requirement. To this end a possible multi-stage route to development and deployment has been discussed. Some additional stages are likely to be needed in the process, which would need to be managed very carefully.

The overall conclusion is that there is enough promise in a spatial approach to bandsharing between radar and communications in the S-band, particularly given the potential economic benefits, to justify further work in this area. The next stage would be a detailed feasibility study examining the link and interference budgets for an initial putative combined system concept.

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14 GLOSSARY

ATC	Air Traffic Control
CDMA	Code Division Multiple Access
ECCM	Electronic Counter Counter Measures
EIRP	Effective Isotropic Radiated Power
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FH	Frequency Hopping
HIRTA	High Intensity Radio Transmission Area
MIMO	Multiple Input / Multiple Output
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
TDMA	Time Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

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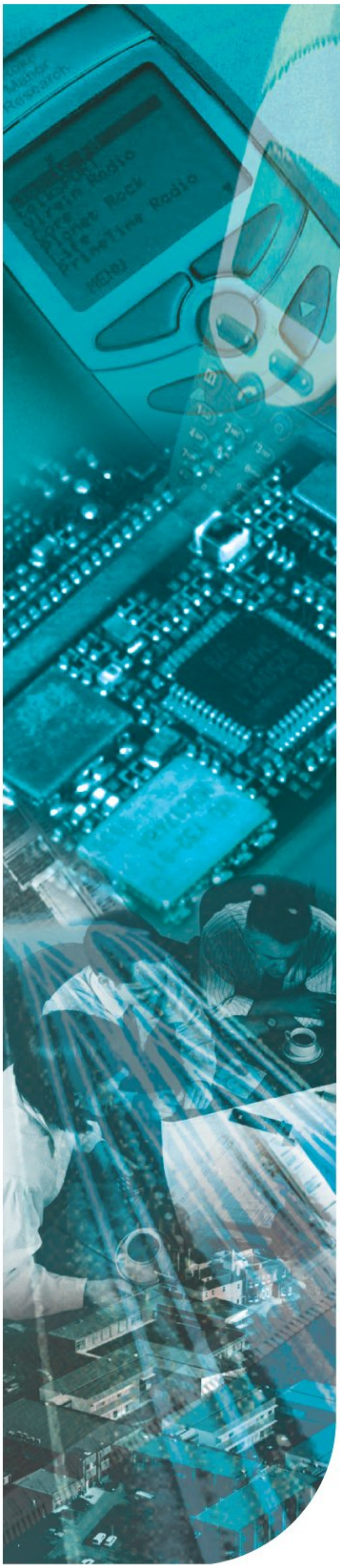

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