Licensing Spectrum

A discussion of the different approaches to setting spectrum licensing terms[1]

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[1] The text in some sections of this paper is based heavily on the SUR Guide published by Ofcom at http://www.ofcom.org.uk/radiocomms/isu/sursguide/ - more details are given in the appropriate sections. This document provides the same information on SURs as provided in the Guide, with some minor changes of terminology and drafting. It adds additional material which explains other licensing methods and compares them with SURs.

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Contents

Part One: Introduction

1. Why licence?

The need for licensing restrictions

A key reason for managing spectrum is to ensure that licence holders, such as cellular operators, do not suffer harmful interference. To avoid interference users are given licences which set out in some form their 'usage rights'[3]. It is important that neighbours both in geography and in spectrum are given compatible licences – i.e. that they do not cause excessive interference to each other.

In granting a licence, rights to transmit are capped in some form or other to limit the risk licence holders suffer significant interference. For example, if users have no restriction on the signal levels they are allowed to transmit outside of their designated bands, they may transmit high levels, to the detriment of neighbouring users.

However, restrictions tend to reduce flexibility by preventing particular types of deployments or particular technologies. Hence, it is important to find the right balance between preventing interference and restricting alternative uses.

Historical licence restrictions[4]

Historically, licences have controlled transmitter parameters such as the maximum power that can be transmitted from any given transmitter. They might do this directly, by providing a so-called "mask" that shows the maximum power levels that can be transmitted both inside of the band that a licence holder has been assigned and also outside of this. Alternatively, they can be stated in terms of a particular technology (e.g. 'GSM') where the technology specifications themselves then provide a transmitter mask that must not be exceeded.

Transmitter parameters provide some guide as to the interference caused since all the interference can only be generated by the transmitters in the network. However, they are only a loose guide. The interference that a neighbour will experience will depend on factors such as how close they are to the base station, the height of the base station, the antennas in use and perhaps most importantly, the density of the base stations. For example, the total interference experienced from a network of TV transmitters is much lower than from a network of cellular base stations, despite the fact that many of the TV transmitters use much higher power than the cellular base stations. This is because the density of the cellular base stations is at least an order of magnitude greater than for the TV transmitters. Because transmitter masks say nothing about base station density, and often nothing about other parameters such as height, the level of interference that might be experienced by a neighbour can vary dramatically for any given transmitter restriction.

Despite this shortcoming, transmitter restrictions have worked adequately for around 100 years. This is because regulators have ensured that like uses and technologies are placed adjacent to each other. Further, like uses tend to have a similar density of deployment. So, to take an example, in the case of cellular networks, as subscriber numbers have grown, the number of base stations deployed has also increased. In practice, this increased density has generally not caused interference problems[5] because neighbouring licences are also

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[3] These are sometimes termed "property rights" because there are many analogies with the rights that land owners have. However, there are also some differences and to avoid confusion the term "usage rights" is preferred here.

[4] This section is based predominantly on part of Section 2 of the SUR Guide published by Ofcom.

[5] An exception to this is Nextel in the US which was adjacent to public safety use. As Nextel became successful it increased its transmitter density, however the public safety organisation had no need to

specified in the same manner and as one operator has increased the number of base stations, so have all the others. Also, operators have tended to coordinate deployments with their geographic and spectrum neighbours to reduce the impact of interference. This ‘symmetry’ of use turns out to be inherently resistant to interference because technologies are typically designed to work well when neighbours are using the same technology with similar deployment density.

A changing environment

In the last decade, many have concluded that the approach of selecting technologies and uses is inappropriate and that licence holders should have licences that are technology and usage-neutral, allowing them to deploy the system of their choice, and to change their deployment as circumstances or technologies change. The problem with this is that it might remove the “symmetry” of use that has enabled the system of controlling transmitter parameters to work so well.

For example, imagine two neighbouring operators both deploying TV broadcast networks. If one were to decide that a mobile TV network would now be more appropriate they might dramatically increase the density of their base stations in order to enable street level and indoor coverage to mobiles. This would substantially increase the interference into the remaining TV operator to the extent that something like 20% of TV viewers would no longer be able to receive a signal. This will generally be unacceptable. Many other similar examples can be imagined.

So, if change of use and change of technology is permitted, there is a serious risk that if transmitter parameter restrictions are used then significant interference might occur when operators change their usage. If operators want protection against this risk then a different form of licensing is needed.

In summary, existing licences can be characterised as only weakly controlling interference. To date, this has only resulted in a few interference problems because when neighbours have similar technologies and deployments transmitter restrictions are adequate. But now that this ‘interference protection’ has been removed to allow greater flexibility the lack of control of interference in traditional licensing arrangements is insufficient to protect license holders from interference when their neighbours change usage. If operators want protection against interference in the future then a different form of licence is required.

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increase its transmitter density. The result was interference to the public safety network and a need to move Nextel to a different frequency band.

2. Types of interference[6]

Introduction

There are broadly three ways that one licence holder (let us term them “A”) can interfere with another (“B”) as shown in Figure 2-1. Each of these mechanisms needs to be controlled by licensing so it is important to understand the differences between them.

1. **Geographical interference**. In this case both A and B are using the same frequencies but in different locations. If A moves too close to B then signals from A’s transmitters can interfere with reception on the edge of B’s coverage area. (Top arrow in Figure 2-1.)
2. **Out-of-band interference**. In this case, A and B are located in the same geographical area, using separate but nearby frequencies. If A’s transmissions in its own frequency bands “spill out” into neighbouring bands then they can be received by B’s receivers as interference. (Central arrow from F2 to F2 in Figure 2-1.)
3. **In-band interference**. Again, A and B are located in the same area with nearby frequencies. In this case, B’s receivers are not perfect and also pick up some of the signal A transmits in its own bands causing interference. (Left hand arrow from F1 to F1 in Figure 2-1.)

Each of these is described in a little more detail below and shown in Figure 2-1.

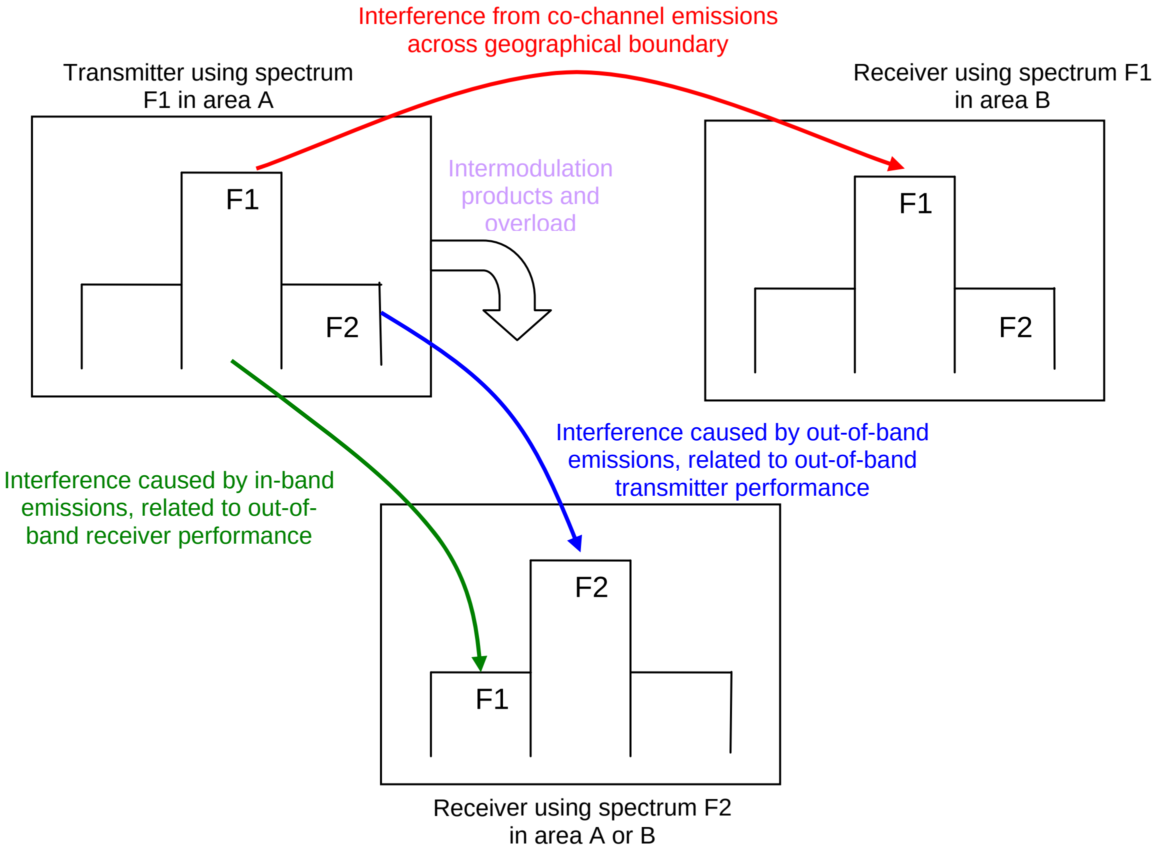

Figure 2-1 : Different types of interference

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[6] This section is taken from Section 2 of the SUR Guide.

Geographical interference

This is the simplest to understand. Unless there is sufficient distance between the edge of the coverage area for A and the edge of the coverage area for B, there is potential for interference. Hence, often a “guard zone” is established between the coverage areas of operators using the same frequencies to allow their signals to decay to a sufficiently low level that they do not cause interference.

Out-of-band interference

When a transmission is made on a specific frequency, the energy transmitted normally extends across a much broader band. This is shown in Figure 2-2 for GSM where the assigned band extends by 100kHz each side of the zero point, but emissions continue well beyond this.

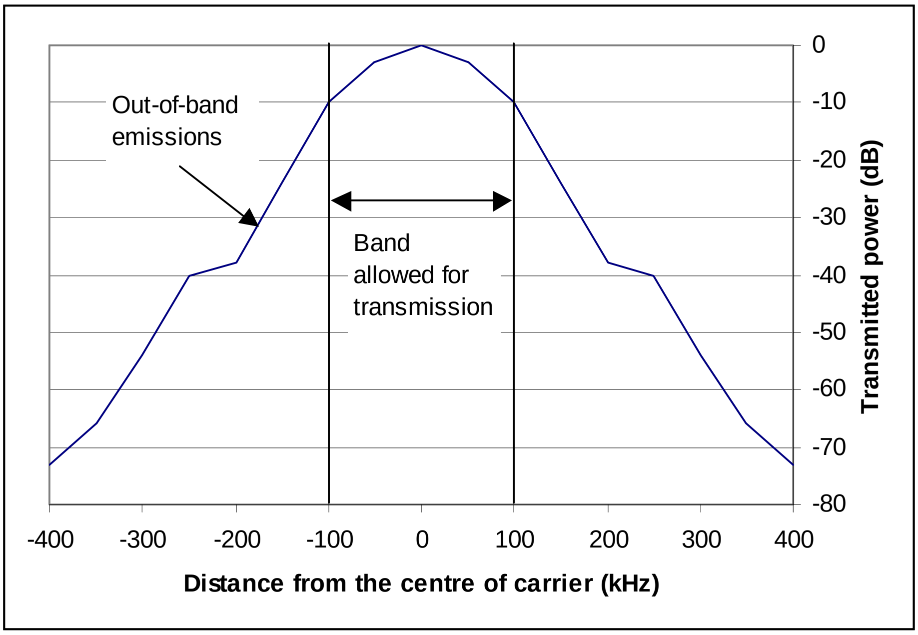


Figure 2-2 : Typical radiation of energy by a cellular transmitter showing overlap into adjacent channels

The degree to which energy is radiated in nearby bands can be controlled by:

- Reducing the system capacity by lowering the transmitted data rate which narrows the overall pattern of radiated energy.
- Increasing the system costs by employing tighter filtering.

Both of these factors reduce the economic value of the spectrum to the licence holder. The overall value of a band comprising many licences can be maximised if licence holders are allowed to transmit a small but significant level of interference into neighbouring bands. Value is maximised if the value of the increase in capacity and / or reduction in equipment cost enabled by the less restrictive interference limits is greater than the cost of the loss of capacity or increased equipment cost that the neighbour suffers. Finding the point of maximum value is complex and is specific to technologies and uses.

In band interference

In the same manner that it is impractical to filter transmissions very tightly, it is also impractical to filter received signals very tightly. Therefore, a radio receiver, tuned to a particular channel, will also receive signals transmitted in neighbouring channels. The neighbouring signals will be much reduced in strength by the filter in the receiver, but will not be totally removed. The ability of the receiver to filter such signals is known as the adjacent channel selectivity. Problems occur in practice when a receiver is far from its associated transmitter but close to a transmitter operating in a neighbouring band. The wanted signal will be very weak, while the signal in the neighbouring band will be very strong. Although the neighbouring signal will be attenuated by the filter in the receiver it may still be sufficiently strong to cause interference. This is often known as a “hole” since it causes holes in the coverage plan of a network to occur around their neighbour’s transmitter sites.

The current solution to this problem is to limit the power that a transmitter is allowed to emit in its own frequency band, termed the in-band power. Knowing this limit, the designer of a radio receiver can determine the maximum difference in signal levels that the receiver is likely to experience and can design the filter appropriately. Value is maximised when the combined costs of:

- higher specification filters in the receivers of operator A, and
- additional base stations to achieve the same coverage as one higher power base station for operator B

are minimised. Again, this is a complex calculation that varies according to technology and usage, and even according to the number of subscribers.
The combined effects of in-band and out-of-band interference are shown in Figure 2-3.

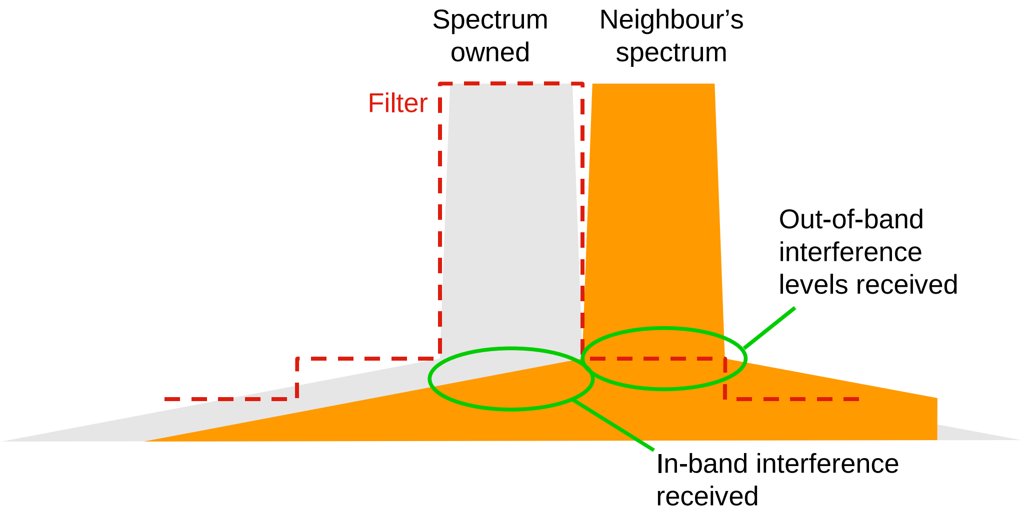


Figure 2-3 : Combined in-band and out-of-band interference effects

Overall levels of interference

The discussion above has shown that there are actually two factors influencing interference. The first is the power levels that a licence holder is allowed to transmit and the second is the density of transmitters. So, for example, even if a licence holder did not increase the power they transmitted at, simply introducing more transmitters would increase the total amount of signal emitted, resulting in increases in both in-band and out-of-band interference.

Uplink and downlinks

A case of additional complexity is when an uplink is changed to a downlink, vice versa or either is changed from frequency division duplex (FDD) to time division duplex (TDD). Consider first the case of a downlink (base station to mobile transmission) channel which has a downlink owned by a neighbour adjacent to it. The interference that a neighbour will experience will be in their handsets and will arrive from a base station which will often be many hundreds of metres away. Now imagine that the downlink channel is changed to an uplink (mobile to base station transmit). Now the interference the neighbour experiences is coming from mobiles that may only be a metre or so away from one of their mobiles. Such interference is typically more damaging than downlink interference and the reason that guard bands or “restricted channels” are often inserted between downlink and uplink.

The case of an uplink is similar. With two neighbouring uplinks the interference that a neighbour sees at their base station will come from other mobiles located throughout a cell and transmitting with relatively low power. Now, if the uplink is changed to a downlink the interference will come from another base station which will be transmitting at higher power levels than a mobile and will also typically be located above the urban clutter, perhaps with a direct line-of-sight to the neighbour’s base station. Again this type of interference is typically more problematic than for two adjacent uplinks.

Finally, the case of TDD is a subset of one of these changes. For example, imagine a downlink channel changed to TDD. A neighbour will now see a mix of interference alternating between downlink transmission and uplink transmission as the TDD channel cycles between downlink and uplink mode.

Some licenses explicitly restrict channels to be either a downlink, uplink or TDD channel to prevent these types of changes occurring. However, an ideal licensing system would not prohibit them, but would ensure that they could only be implemented at appropriately reduced power levels such that the overall interference experienced remained unchanged.

3. Different approaches to licensing

Introduction

There are many different approaches to licensing spectrum. Broadly these can be divided between regulatory limits and user-controlled scenarios. In the regulatory case, the regulator provides licenses that attempt to control the interference between users such that they are able to offer reliable services. In the user-controlled cases the regulator provides fewer restrictions, either relying on users to coordinate between themselves or, as is the case with licence-exempt usage, only providing very weak control over possible interference levels. In this document we are more concerned with regulatory approaches although we touch upon the user-controlled cases briefly in this chapter.

Regulatory approaches

All the regulatory approaches seek to control the interference caused to neighbours. They do so either by:

- Placing direct restrictions on the transmitters, resulting in indirect restrictions on the levels of interference experienced by neighbours, or:
- Placing direct restrictions on the levels of interference experienced by neighbours (and as a result, indirectly restricting the transmitters).

We can term these transmitter restrictions and interference restrictions, respectively.

These approaches are linked but different. The reason that the approaches are different is because of the indirect linkage between transmitters and interference. There is clearly a linkage in that the interference can only be caused by transmitters and the more power a transmitter emits the higher the interference experienced by a neighbour. However, the linkage is indirect because the interference experienced depends on the propagation path between the transmitter and the victim. This propagation path in turn depends on the distance from the transmitter to the victim and the nature of any obstacles between them. So, if a neighbouring receiver is closer to a transmitter it might generally expect to receive more interference. The implication of this is that a licence holder could stay within its transmitter restrictions, such as the maximum power level, but by deploying a denser network of transmitters increase the interference experienced by a neighbour. In this case, the transmitter restriction provides only weak control over the interference experienced by a neighbour.

There are different approaches that can be adopted to both transmitter and interference restrictions, discussed briefly below and in more detail in subsequent sections.

All approaches can be enhanced by coordination between neighbours. If neighbours are prepared to work together they can ensure that their networks are planned to fit together optimally. This might involve avoiding the use of adjacent channels in the same area and co-siting transmitters. Ideally any licensing approach should facilitate coordination and allow for relaxed restrictions where effective coordination occurs.

Transmitter Restrictions

Any number of restrictions can be placed on transmitters. At their simplest, these tend to be limits on the power that can be transmitted by an individual transmitter. These power levels can cover just the band owned by the licence holder or can be extended to cover neighbouring bands as well. The latter are often known as “spectrum masks” or “block edge masks” (BEMs).

Further restrictions could be envisaged to address the problem of transmitter density mentioned above. For example, the maximum number of transmitters per unit area could be capped. However, this ignores the fact that some networks deploy a mix of high and low power transmitters – an extreme example of this would be a cellular network comprised of thousands of relatively high power base stations and millions of very low power femtocells. Simply restricting transmitter density might prevent a relatively harmless use of such low power cells. Of course, low power transmitters could be excluded from such a transmitter density restriction, but deciding where to draw the line could be difficult.

An enhancement to this approach would be to cap the transmit power per unit area. In this approach, the sum of the transmitter power across all transmitters in a given area would be limited. This is a further improvement, coming closer to directly controlling the interference experienced by neighbours. However, it may be inaccurate in some cases. For example, the interference caused by a base station in an urban area mounted above rooftop level will be much higher than one mounted below rooftop level. This aggregate transmitter approach would not take this effect into account.

Transmitter restrictions limit the size of any “hole” that can be caused in coverage since this is directly related to the level of power transmitted. However, because there is no restriction on the number of transmitters, equally, there is no restriction on the number of holes.

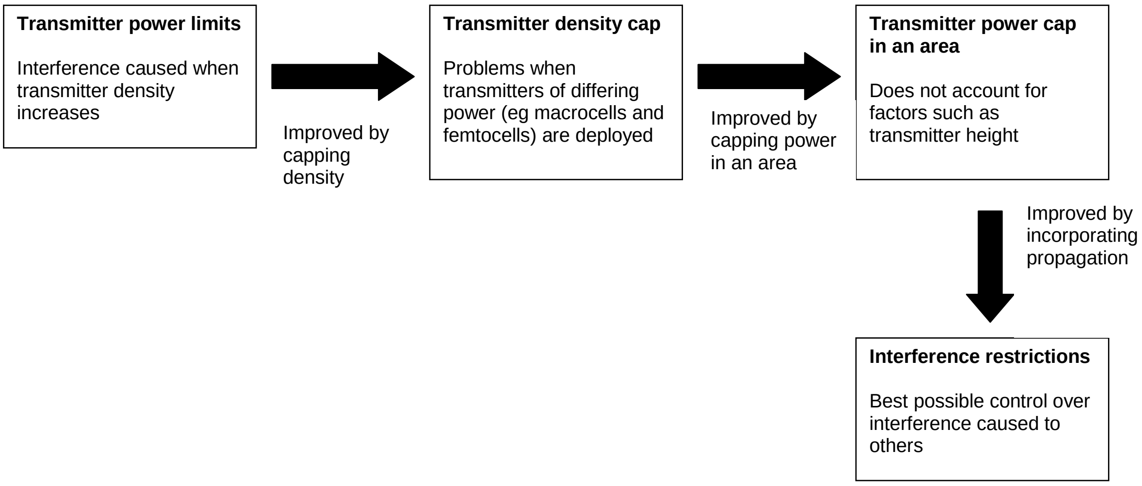
Interference restrictions

The alternative to placing restriction on transmitters is to place restrictions on the interference levels that can actually be caused. In principle, this is a superior approach because it is these interference levels that will cause problems for a licence holder and that they will wish to see capped. As seen above, using transmitter restrictions cannot accurately control interference levels, so it is better to control them directly.

The problem with such restrictions is that they are more difficult to specify and to validate. Since a receiver could be located anywhere, the interference levels need to ideally be measured across all possible receiver locations and then suitable statistics derived. Clearly, measuring at all locations is not possible but good approximations can be achieved via measuring or modelling at a number of selected locations and then making use of statistical analysis.

Interference restrictions place no limit on the size of any particular “hole” since they do not cap the transmitter power. In practice, this is limited by factors such as health and safety considerations or the need for a balanced uplink and downlink. However, they do limit the total area of all the holes across a network since holes are directly related to interference levels.

In fact, each of these different licensing methods can be seen as a progression or enhancement as shown in the figure below.



The most well-developed form of interference restrictions are Spectrum Usage Rights (SURs), developed by Ofcom, the UK regulator.

User-controlled restrictions

Alternatively, the regulator might not attempt to directly control interference, leaving this to varying degrees up to the user. This tends to result is a rather different licensing environment and resulting use of spectrum, with typical applications being short range.

Licence exemption and light licensing

In licence exempt spectrum users do not need a licence. Anyone with suitable equipment can use the spectrum. Typically there are requirements that the equipment transmits at relatively low power levels and there may also be additional “politeness” requirements that ensure access to the spectrum is shared equitably amongst all. Licence exemption provides no guarantees about interference levels. It is possible that a large number of devices try to access the spectrum and cause significant interference between them. This is a risk that the users bear in gaining free access to spectrum. It is because of this risk that few networks are rolled out in this spectrum.

Light licensing is an approach where users do require a licence (unlike licence-exemption) but this licence is typically very low cost and available on request to anyone. Users then have to register their use of the spectrum in some way, such as through a database containing parameters of each of their transmitters such as their location and power levels. Varying degrees of control are then possible. At the least constrictive level the database is simply there to allow new entrants to take account of existing use when siting their equipment should they wish to do so. At the most constrictive, a new entrant causing interference to a registered user could be required to correct the situation. Many variations between these levels are possible. Light licensing does not attempt to control interference through technical licence terms, instead relying on resolving any interference after it has occurred.

Coordination between users

As mentioned earlier, if users are prepared to coordinate their deployments then, in principle, licence conditions are no longer necessary. Instead, the users can determine between them the optimal way to site their networks and the technologies they should use. Many neighbours do cooperate to varying degrees – for example cellular operators tend to coordinate at boundary areas to avoid the use of neighbouring channels. However, coordination without any over-arching licensing framework can be problematic when there is disagreement between users. Licence holders generally prefer that their neighbours have restrictive licensing conditions in case these neighbours decline to coordinate or there are resulting disagreements between them. If the neighbours are able to coordinate then licensing conditions can be relaxed appropriately.

Comparison of the different approaches

A comparison of the different approaches against some key variables is provided below.

Approach	**Risk that licence holders might suffer interference**	**Ease of use**	**Can be modified if neighbours negotiate**	**Control of holes**
BEM	High	Very simple	No	Size limited but not number
BEM with transmitter density	Moderate	Moderate	Density cap can be relaxed	Size and number limited
Transmitter power per unit area	Moderate	Moderate	Power cap can be relaxed	Size and number limited
Interference restrictions	Low	Complex	Interference level can be changed	Total area limited
Coordination	High unless coordination is effective	Depends on agreement	Depends on agreement	Depends on agreement
Licence-exempt / light licensing	High	Depends on scheme selected, normally simple	Generally not as there are too many neighbours	None

As the table shows, there is a trade-off between the level of interference control achieved and the ease of use of the scheme. This is explored further in the next section.

4. Which licensing approaches to use where

Introduction

As suggested at the end of the previous chapter, as the control of interference increases so does the complexity of the scheme. This suggests that it may be appropriate to use different approaches in difference cases. This is considered further in this chapter, starting with an assessment of the cases where interference might be problematic.

Understanding of interference issues

Figure 4.1 provides a useful way to understand possible frequency interference issues (geographical issues are not covered in this chapter). It shows the cumulative distribution functions (CDFs) of the levels of in-band interference that might be caused by a range of different network types in the downlink direction.

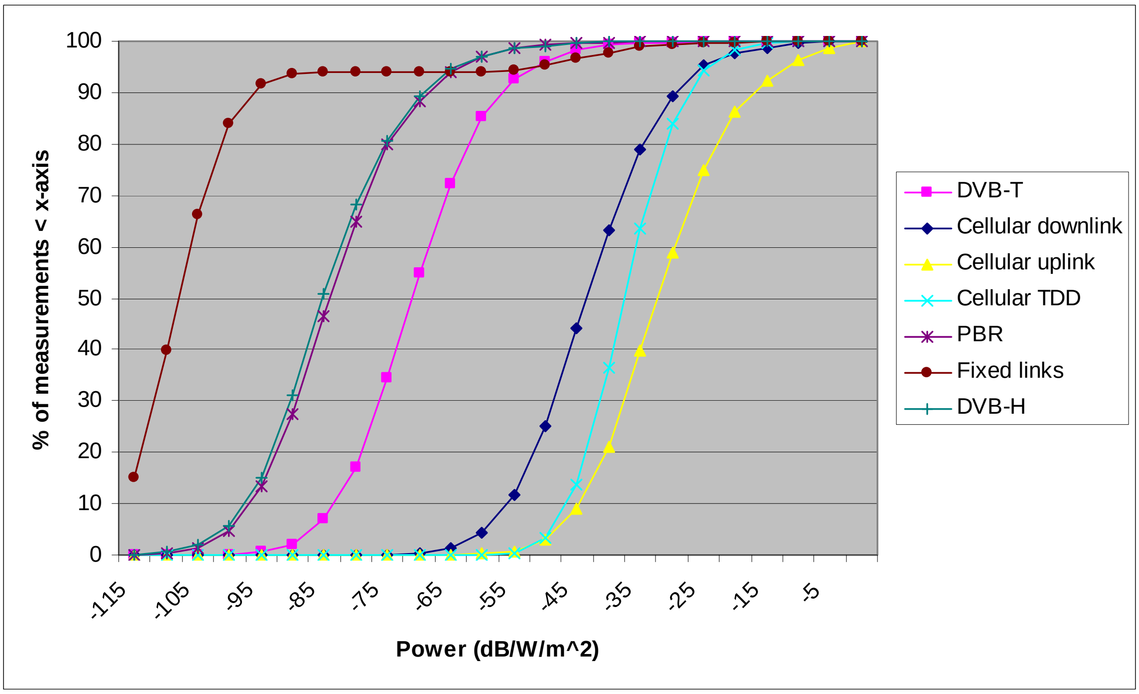


Figure 4.1 – Distribution of the interference power produced by a range of services (cumulative)

The figure shows that:

- The highest frequency interference levels are created by cellular systems. This is because of the relatively high density of base stations in urban areas.
- DVT and PBR systems create around 30dB less interference due to their substantially lower transmitter density.
- Fixed links are another 30dB below this, due to the relatively low density and directional nature of the antennas.

Interference occurs from one network (network A) to another (network B) due primarily to:

- In band interference from network A being received as out of band interference in network B (because the filters in the receivers of network B are imperfect).
- Out of band interference from network A being received as in band interference in network B.

The impact of increased interference will depend on a how much margin the “victim” network has. If the victim network is operating with a high signal to noise ratio and has receiver filters that provide substantial margin then the impact of increased interference in the neighbouring bands may be minimal. Alternatively, a network operating close to the limit, or where any incremental signal strength is used to send higher data rates via higher order modulation might suffer immediate effects as a result of any increase in interference. Without a detailed knowledge of the characteristics of network B it is difficult to determine the impact of any increased interference. However, the discussion below shows some possible outcomes.

Areas where control of interference is most valuable

Interference problems are most likely to occur when a neighbour makes a change of use which results in an increased interference. Broadly these are likely to be:

- Any change to a fixed links band (eg to cellular, broadcasting or most other uses).
- A change from broadcasting or PMR to cellular, or potentially to DVB-H if a high density DVB-H network is envisaged.

Conversely, changes to cellular networks are less problematic, although a change from a downlink to an uplink or to TDD could cause issues if it were allowed in the licence conditions.

As an example, consider a DVB-T network, which previously had a DVB-T channel adjacent to it. If this adjacent channel were modified to cellular downlink then some estimates[7] suggest that around 10% of TV receivers would suffer interference. Given that the PSB DVB-T network in the UK is engineered to provide better than 98.5% coverage then 10% interference would be a substantial loss of subscribers. The cost of correcting this would depend on the approach adopted, but if it required an enhanced broadcasting network it seems likely that it could be many hundreds of £million. If the neighbouring channel were used for cellular TDD then estimates[8] of interference occurring in up to 40% of cases have been made. Under a BEM approach the DVB-T operator would have a licence enabling them to transmit many kW of power. This would in no way restrict them deploying a cellular network. However, if they had an interference-based licence the interference levels generated by cellular would exceed their licence terms, preventing such a change of use.

A second example is a change of cellular use from FDD to TDD. Note that many licence conditions will prohibit this, including the proposed terms for the Ofcom 2.6GHz licence[9]. However, let us consider the case where there is no prohibition on this. Imagine two cellular operators A and B using neighbouring blocks of spectrum for downlink purposes. Now imagine operator B decides to change their downlink to a TDD link. If an unrestricted TDD

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[7] Masons – “Digital dividend – mobile voice and data (IMT) issues”, October 2007. See http://www.ofcom.org.uk/consult/condocs/ddr/statement/Mason1.pdf

[8] Aegis – “Interference analysis of mobile WiMax, DTT and DVB-H”, 2007. See http://www.ofcom.org.uk/consult/condocs/ddr/statement/Aegis2.pdf

[9] Which, of course, implies that under these licence conditions BEMs are less technology and usage neutral than interference restrictions.

channel is placed next to an FDD channel then interference can result. Analysis[10] shows that, in the absence of interference there is a 5% probability that the FDD downlink throughput drops below 205 kbits/s over the cell area. However, when in the proximity of TDD terminal stations transmitting there is a 5% probability that the throughput drops below 55 kbits/s over the cell area. This represents a significant decrease in the network capacity and the services that can be offered and is the reason why many regulators decided to restrict the power levels that could be used in TDD blocks adjacent to FDD and to place additional restrictions on change of uplink and downlink arrangements in the 2.6GHz licence.

Under a BEM approach the power restrictions would be set for base stations. Since mobiles transmit with less power than base stations, then these restrictions would not constrain mobile use in any way so a change to TDD would be allowed. Under an interference restriction approach the interference level at the mobile would exceed that allowed and the change would be prevented.

Areas where control of interference is less valuable

As shown by the earlier analysis, interference is less likely to occur under two scenarios:

- All the users in a band are already using networks that deliver high PFD levels and therefore a change of use of their neighbours to a network causing an even higher PFD level is not plausible. This would be the case typically for cellular networks.
- All the users in a band are using similar networks and there is no likelihood of a change of use.

The first situation might occur in bands used entirely by cellular operators, such as the existing 900MHz, 1.8GHz and 3G bands, and likely in the 2.6GHz band after auction. It is less clear where the second might occur since it would be difficult to be certain that a change of use would not occur over the next 10-20 years that some licences last.

Licensing individual transmitters

The discussion up until now has assumed licences that cover substantial areas – perhaps the whole of a country or region. However, there are some applications where users require only a single transmitter or a small number of transmitters. These include private radio systems such as those used by taxi companies and fixed links used to provide a connection between two individual points.

While it is possible to licence individual transmitters using any of the approaches discussed so far it tends to be excessively complex and expensive. Where a single transmitter has been authorised no "change of use" that impacts on deployment is possible (because only a single base station is allowed) and the transmitter power tends to be capped. Other users can then be carefully planned around this transmitter using modelling tools to understand where the same channel can be reused. This planning is mostly performed by regulators although it could be undertaken by a third party "band manager".

In this situation it is often more helpful to think of the regulator or band manager owning a national licence for the band which might be subject to transmitter or interference restrictions. They then sub-licence individual transmitter sites on whatever basis they prefer, ensuring that in doing so they remain within their overall licence terms. The sub-licensing might be performed by computer modelling with particular targets of interference levels to be

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[10] Ofcom, "On the impact of the interference from TDD terminal stations to FDD terminal stations in the 2.6GHz band", published at http://www.ofcom.org.uk/consult/condocs/2ghzregsnotice/tech.pdf. See Figure 5 and accompanying text.

met or it might be achieved through database registration of existing users with new users required to show they do not cause interference to those already registered.

So in summary, individual transmitters are best licensed on a simple location and power basis by a regulator or band manager which might itself have a more complex licence for the overall band.

Conclusions

This section has shown that different types of spectrum use generate significantly different levels of interference. If there is a change of use from one that generates a relatively low level of interference, such as broadcasting, to one that generates a relatively high level, such as cellular, then the potential for interference to the neighbouring users is severe – in some cases reducing capacity by 75%. In such cases BEMs do not prevent such changes and so their use would place significant risk of interference where technology and usage-neutral rights are awarded unless additional licence restrictions are added. Interference restrictions however, as a result of the fact that they constrain interference itself, would prevent such changes of use (unless the neighbours agreed and the licence conditions were changed).

Equally, there are cases where there is little danger of interference occurring under plausible change of use scenarios where the additional complexity imposed by interference restrictions may not be warranted. In particular, bands used for cellular networks would appear to fall into this category.

In the following sections we consider transmitter and interference licensing in more detail.

Part Two: Transmitter Restrictions

5. Block edge masks

Introduction

The concept of a BEM is simple – it is a restriction in maximum transmitter power allowed both within the licence holder's band and outside of it. In this section we explore how the levels are set, how compliance can be assessed and the problems with BEMs.

Setting the levels

If BEMs are used to restrict interference then the levels set within the mask need to be set accordingly. Since the levels themselves do not define the interference received, as discussed in previous sections, BEMs can only be set in a meaningful way with reference to a particular scenario. Of course, this means that the BEMs may not be appropriate if the scenario changes, which is a key criticism of this approach which we will return to at the end of this section.

Definition of a scenario typically needs to start with a predicted usage such as cellular or broadcasting. From this assumptions can be made as to the most likely technology and type of deployment.

For example, if we assumed that a frequency band was most likely to be used for cellular communications we might predict that the most likely technology was W-CDMA and that interference was most likely to occur in city centres where the highest density of users was likely to occur.

The next stage is to determine the levels of interference that are acceptable. This is somewhat subjective, but, for example, it might be suggested that interference should not occur more than 100m away from a neighbour's base station or more than 2m away from a neighbour's mobile. Even then it can be difficult to define what is meant by "interference" – is it a complete loss of communications or just a degradation in data rate? If the latter, what percentage constitutes interference? Once these questions are resolved – typically through discussion with stakeholders, then various approaches can then be used to determine the BEM levels that would achieve this particular probability of interference.

The simplest approach is to use "minimum coupling loss" (MCL). This considers one transmitter and one receiver separated by the minimum distance determined (eg 2m for mobiles). It looks at the strongest signal that might be received in this situation, assuming that there are no obstacles in the way. Through an understanding of the signal level that will just cause interference it can then determine the maximum transmitter power that should be allowed.

A more complex approach is to use Monte Carlo modelling. In this approach a model that is representative of the two neighbouring networks is established. This would involve fixed base stations and a number of mobiles moving around and randomly making calls. The model would sum up the interference experienced by each mobile and base station as a result of all the activity around them and would assess the degree to which this interference would compromise communications. The results of such a model are statistical – for example they might suggest that there is a certain probability that a call would be dropped due to interference or that on average the data rate achieved per mobile would drop by a certain percentage. The Monte Carlo approach tends to be more complex but leads to results that are more likely to be an accurate reflection of reality.

In either case, the process of setting BEM levels is problematic. It requires significant judgement at many stages of the process from selecting the most likely use and technology through to determining at what level interference is problematic. Often this is controversial and results in lobbying between stakeholders and regulators. There is no right answer and, as we will see below, the final numbers selected may be of little relevance in any case.

Verifying compliance

In principle, verifying compliance is simple. A transmitter is selected and its transmit power levels measured. Those deploying networks have certainty that if they keep their transmit power levels within the limits that they will not breach their licence conditions (however, they have very little certainty about the levels of interference they will receive from others).

In practice, measuring transmitter power levels may not be simple. Power levels vary, particularly where transmitter power control is used, and hence careful averaging may be needed. Connecting up to a transmitter to measure its power is also difficult, requiring a complex arrangement of splitters. Making the measurement may require the transmitter to be taken off-air while appropriate connections are made and to be run in a particular mode when making the measurements.

Problems

The biggest problem with BEMs is that they only protect against interference as long as the assumptions made in their derivation hold. Any change of technology, usage or deployment approach will generally render the derivation of the BEM levels invalid. As has been set out earlier, just an increase in transmitter density above that initially expected, will result in increased interference levels – which in some cases can be seriously problematic.

Even if usage does not change, setting the level of BEMs is difficult and controversial with no “correct” level. In practice, administrations often set the BEM level at one that aligns with the standards body that has developed the technology on the basis that the standards body may have selected an appropriate compromise between interference and effective use of the spectrum. If this level proves to be inappropriate then generally the licence holders will need to find a solution.

6. Transmitter density controls

Introduction

Unlike BEMs, transmitter density controls have not yet been widely implemented – indeed, as far as we are aware there are no licenses of this sort yet in existence. Hence, this section is based on an analysis of what such restrictions might look like were they to exist.

Perhaps the closest existing system is that used in Australia. Here, they do not set a prior limit on the number of transmitters. However, each new transmitter that an operator plans to deploy must be approved and registered. During the approval process a qualified engineer assesses whether the deployment would cause interference problems and would therefore, in principle, be able to prevent more base stations being deployed once a certain density had been reached. However, in practice, each new base station tends to be considered in isolation, rather than in combination with the existing base stations, and so a density restriction is not realised in practice.

In this section we consider the various ways that density restrictions might work and how the levels would be set. We also consider compliance issues and likely problems.

Capping transmitter density

The simplest form of transmitter density control would be to add a limit to the number of transmitters per given area on top of a BEM restriction. In this case, the BEM limits need to be set as before and in addition the maximum transmitter density should also be set. If the approach to setting BEMs discussed in the previous section was adopted then there would have been a model deployment scenario, perhaps in an urban area. Based on this scenario, the transmitter density could be calculated and set as an upper limit in the licence. However, this raises the question as to the size of area that the transmitter density should be measured across. This turns out to be somewhat complex and is discussed in more detail below.

The size of the test area

It might be initially envisaged that the transmitter density could be set as, for example a maximum of x transmitters per km^2. But in many cases x might be less than 1. Clearly there will be some km^2 tiles of “test areas” that do include a transmitter and others than do not. Any test areas that do will breach the limit, making it impossible to deploy any base stations! The obvious solution to this is to make the test area larger so that x is greater than one. But even then, deployments might be envisaged where base station sites on a perfect square grid could not be found and so for one particular selection of the test area that is laid on the map the limit is breached, whereas if the test area is moved just a few metres the limit is met. With base station deployment being far from regular in practice it makes sense to select a relatively large value of “x” – the number of transmitters allowed per test area – so that variations of this sort can be averaged out.

However, if the test area is too large, it is possible for a licensee to deploy a very high power transmitter or a network of transmitters within part of the area and still be within its limits when averaged across the whole area. For example, if the test area was all of Southern England then a very high density deployment in London could be averaged out by a lower density deployment in rural areas. This would not afford the protection that the transmitter density cap is designed to supply since a licence holder could still dramatically increase their base station density in urban areas so long as they had a small reduction in the rural density.

So clearly there is a balance to be struck between a test area that is so small that different results can be gained simply by moving it a few metres and so large that it averages substantial variation in transmitter density. In practice, some simple modelling shows that if the test area contains at least 10 transmitters, the variation in transmitter numbers resulting from small changes in the position of the test area is minor. Hence, the test area could be selected as that area measured in km^2 which contains 10 transmitters in the most dense deployment scenario envisaged.

As we will see, defining the test area is a recurring problem for many licensing approaches and we will return to it as we consider alternative schemes.

Measuring the actual density

This approach has the same enforcement problems as BEMs. In addition, there is a need to verify that the density set is not exceeded in practice. Broadly, this can be achieved by requesting transmitter location from the licence holder and using a simple model to verify that there are no areas where the density limit is exceeded. However, this requires trusting the licence holder to provide correct data. If there is reason to doubt this then teams may need to visit suspect areas and try to determine where the base stations are located. This can be somewhat difficult as base stations may be disguised and temporarily turned off if the licence holder suspects that an investigation is underway.

Problems

As discussed earlier, capping transmitter density might prevent many sensible deployments. As an extreme example, cellular operators are considering femtocells – small base stations installed in the home. This would dramatically increase the transmitter density and would likely not be allowed under a density cap. However, because they are such low power and contained within the home then the impact of such cells on interference might be minimal. Cellular operators routinely deploy a wide range of cells from high power base stations through microcells and picocells to femtocells. Since the impact of the cell is proportional to the power level transmitted it can be seen that a simple transmitter density cap is likely either to be highly restrictive to the licence holder or to prevent sensible network deployment types.

Capping transmitter power per test area

The obvious solution to the problems of a transmit density cap are to link the cap not to transmit density but to total transmit power within the test area. This then allows for a range of different type of base stations with a large number of low power stations possible if appropriate. The limit could be set in much the same manner as for the transmit density cap by considering the scenario built to evaluate the BEM case and determining the maximum transmit power calculated per test area.

The test area can also be calculated and used in a similar manner to the transmit density cap. However, there may be some risk that the area could become inappropriate over time. For example, if it were initially set assuming that, say 10 base stations would cover a city, then over time a dense network of lower power transmitters was installed in the centre of the city, there might be higher power levels in the centre than at the outskirts as well as perhaps hundreds of transmitters within the test area. This averaging of high power in the centre and lower power on the outskirts might be problematic to neighbours and perhaps a smaller test area would be appropriate. Changing the test area over time is possible, and is discussed in more detail in connection with SURs in the following sections.

Measurement issues are also similar to the transmitter cap case, although in addition to the location the actual transmit power is also required from the operator and potentially might need to be evaluated.

Problems

The use of a maximum power limit per test area overcomes the key problem with the transmitter density cap in that it allows for a range of low and high power transmitters and comes reasonably close to limiting the interference received. However, there are cases when it will be inaccurate, in particular the impact of base stations mounted above rooftop level will be somewhat different from those mounted below this level. Base stations in urban areas will typically cause less interference than similar base stations in suburban areas because the shadowing will be less. This approach could be made more accurate through the use a propagation modelling as discussed below for SURs.

This approach is also relatively poor at preventing changes of use between uplink and downlink. This is because the typical power transmitted by a base station is often greater than the sum of the power of all the mobiles in that cell which could simultaneously access the base station. Hence, a change from a downlink to an uplink or to TDD is not prevented. This could be corrected with additional restrictions preventing this sort of change but this somewhat reduces the flexibility of the approach.

Summary

Transmitter density and power caps are a significant improvement on BEMs as they go some way to prevent the most problematic of the changes of use that could lead to interference problems. They add a certain amount of complexity to the licensing approach and bring some problems of their own. A simple cap on transmitter density would appear overly restrictive given the range of cell types that might be deployed. A cap on power within an area is better, but could potentially be made even more representative of the actual interference level caused if it were linked to a propagation model. If this were done, the result would be to generate interference restrictions as discussed in the following section.

Part Three: Interference restrictions

7. An introduction to interference restrictions[11]

Introduction

This section provides an overview of interference restrictions. Particular points are then discussed in more detail in subsequent chapters.

Form of an interference restriction

An interference restriction specifies signal strength as experienced by a receiver. There are many different ways to express signal strength. Perhaps most common is a power level, for example -85dBm/MHz, however this is frequency dependent and makes assumptions about the receive antenna used. An alternative is power flux density (PFD) which expresses the power at a certain point in terms of watts/m^2/MHz. In practice, these and other approaches are equivalent as long as appropriate care is taken in specifying assumptions such as the antenna used and so the particular term chosen is unimportant.

The PFD term needs to be applied to each of the three different forms of interference introduced in Chapter 2. For geographical interference, the signal level generated, specified in terms of power flux density (PFD), at or beyond the geographical boundary should not exceed a set power level.

For out of band interference the PFD measured at an agreed height above ground level should not exceed a set power level at more than a certain percentage of locations in a set area. The reason for the percentage of locations is that if just one, or a few, measurements were made they might be close to a spectrum neighbour’s base station where the signal level received would be very high. Enough measurements are needed to average over a representative area.

In-band interference can be specified and measured in an identical manner to out-of-band interference. The only difference is that the allowed PFD level would be higher, reflecting the fact that spectrum users are generally allowed to transmit much higher power levels within their bands than outside them.

This, in outline, is what comprises a receiver restriction – a set of three PFD limits corresponding to the three types of interference. The complexity arises in firstly deciding what limits to set and secondly in verifying that they have not been exceeded. Much of the remainder of this part will consider these issues, in this chapter they are discussed in outline.

Setting the initial values

Determining the numbers to put into these licence terms may not be simple. For example, the 3G specifications set maximum transmitter power but not the distribution of allowed interference. To arrive at the interference distribution requires assumptions about the likely use of the band and then the likely transmit power, the likely base station density and some other factors such as base station antenna gain and height and the use of power control mechanisms. These can then be input to a propagation modelling tool which can be used to estimate the interference distribution and hence arrive at the licence terms. Of these assumptions, the likely base station density is most difficult. For systems still in their early

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[11] This section is based predominantly on Section 3 of the SUR Guide.

deployment stage, the final base station density may be unclear, even to the operator. A very similar approach is needed to that which might be adopted for BEMs, as discussed in Chapter 5, other than the output is a set of PFD levels rather than a maximum transmit power.

Getting these values right is preferable but not essential as there are opportunities to modify them after the issue of the licence as described later.

Verifying that licence holders operate within their terms

Perhaps more complex than setting the values is the process of ensuring that licence holders adhere to them. With the transmitter restriction approach this was relatively simple – it was just a matter of checking whether transmitter powers were below a threshold. However, such a check was also of relatively little value, since, as already explained, transmitter powers are only weakly linked to the interference caused. With interference restrictions the actual interference caused, or some approximation to it, must be assessed in order to verify compliance.

One key decision is whether to verify by measurement or modelling. Measurement would involve using radio receivers to make actual measurements in a number of locations. It is accurate, if done correctly, because it does measure the actual interference caused, but could be expensive and time-consuming to undertake, especially where signal levels vary over time and so substantial averaging is needed. Modelling estimates the level of interference using propagation modelling tools. It approximates to the interference caused, because no models are perfect, but can be performed quickly and at much lower cost than measurements. Also, because it accords to the manner that networks are planned, it makes it simpler for licence holders to verify as they plan their network that it will not exceed its licence terms. Conversely, with measurement there is some risk that they deploy a network based on their modelling tools only to find that in practice it exceeds their licence terms.

Clearly there are benefits from either approach – measurement is more accurate but modelling is simpler and cheaper. It would be possible to adopt different approaches in different frequency bands and the approach could be changed over time if needed. At present, the general view is that modelling is more appropriate – this is discussed in more detail in Chapter 10 and the modelling itself is discussed in Chapter 11.

This then leads to a need to specify exactly how the modelling will be done so that all licence holders end up with the same results for a given network deployment. Defining the modelling falls into two parts – firstly specification of the propagation algorithms and necessary databases and secondly specification of the process and assumptions that need to be made.

At the heart of a modelling process is a propagation algorithm that takes as an input the network deployment parameters and produces as an output predicted signal strength levels. There are many propagation models available. Some are standardised, predominantly by the ITU, others proprietary. Different models often apply for different frequency bands and sometimes for different services. It is more accurate to consider each band separately and select a model that fits most closely to the likely usage and frequency range of that band. Because models often have options or variable parameters, these need to be specified in detail so that all parties will get identical results when using it. Finally, models make use of geographical databases (which show terrain height) and clutter databases (which divide areas into different usage types such as urban, forest, etc). All licence holders need to use identical databases so the supplier and version number of these needs to be set in the licence.

The next stage in the process is to define the test area over which the restrictions will be computed. The issues here are basically the same as those discussed in Chapter 6. By way of reminder, if the test area is made very large (eg the whole country) then very high levels of interference could be caused in some areas and low interference levels in others. The averaging process would then allow the licence holder to be within the terms of their licence but this would not provide any real protection to neighbours. If the test area is made very small, so that, say it only include a part of the coverage area of a single base station, then placing this measurement area near the centre of the cell would deliver very different results from placing it near the edge of the cell. This would lead to excessive variability in results which is not desirable. The solution is to find an area somewhere between these extremes. Modelling suggests that if the area includes of the order of 5-10 cells then there will be little variability regardless of where it is placed but equally this should avoid any significant averaging effect. Where a licence holder has a network comprising less than 10 cells (perhaps just a single transmitter) then the modelling area should be their complete geographical licence area.

Unfortunately, the size of cells varies, both with geography and with time as operators split cells. Imagine a test area that covered 10 cells of a cellular network in a city centre. In rural areas it might only cover a single cell leading to the problems of variability as discussed above. If the area were made large enough to cover 10 rural cells it might cover not just the urban area but a substantial surrounding area leading to the averaging problem discussed.

So it is not possible to define a test area in terms of its dimensions. Instead, it needs to be defined in terms of the number of base stations it contains such that it can vary both by geography and over time as network density increases. There are many ways that such a test area could be defined but broadly when given a location where interference may be problematic an area needs to be drawn around this location such that it includes at least 10 cells. It is also desirable to avoid an infinite number of possible tests. If any location could be selected then an operator wishing to verify that their network was compliant would need to test every possible “seed point” of which there could be an infinite number. This can be avoided by selecting the nearest intersection point of a 1km (or similar) grid square as used by mapping agencies.

Uplink and downlink

Because interference restrictions have the ability to control interference directly, they can ensure that any change from uplink to downlink or vice versa does not result in an increased interference. Imagine a downlink that is allowed to cause a certain amount of interference to a neighbour. This can be changed to an uplink as long as the amount of interference caused is unchanged. However, to ensure this some mechanism of modelling the interference caused from an uplink is required. This section considers how both downlink and uplink usage can be modelled.

For a downlink the first step is to input into the model the location of the base stations, their height, transmit power and antenna patterns (even downtilt can be included depending on the level of accuracy required). Then the modelling tool needs to assess each “pixel” within the measurement square. A pixel might be say a 50m x 50m square. For each pixel the tool determines the signal strength from each base station using the agreed propagation algorithm and adds them to form the total predicted PFD for the pixel. Once this has been done for all pixels it can be determined whether the licence terms have been exceeded - this occurs if there are more than a given percentage of the pixels (eg 10%) with a modelled PFD above the agreed limit.

If it is an uplink then more assumptions need to be made since we cannot know where all the mobiles are and whether they are transmitting at any given time. What we do know is the number of base stations operating in receive mode on that frequency and we have some understanding of the uplink capacity of each base station. Knowing this sets a limit on the number of mobiles that can transmit simultaneously for any given data rate. How we proceed from this point depends on the balance required between accuracy and simplicity of modelling.

A relatively simple approach is to select the data rate for a likely representative service[12] (eg voice for cellular) and then set an assumed maximum number of mobiles that could simultaneously access a cell assuming a fully loaded network in the vicinity. This will, of course, be an approximation to reality. Each mobile would then be distributed evenly around the cell and assigned a power level according to its distance from the base station. The next steps depend on whether the neighbouring service which is concerned with the interference caused is also an uplink service or a downlink service.

If it is an uplink then we are interested in the interference caused into the base stations. So for each pixel in the measurement square we can assess what level of interference a base station placed in that pixel would experience by summing the interference from all the mobiles across the measurement square (although in practice only those few mobiles nearest the base station would make any difference). We can then repeat for each pixel and determine whether the licence criteria have been met.

If it is a downlink then we are interesting in the interference caused into mobiles. In this case, the interference will typically depend on the probability of a transmitting mobile and receiving mobile being in close proximity. We know the density of transmitting mobiles so we can determine the probability of a receiving mobile being within any given distance from a transmitting mobile and the interference they will receive as a result. This interference probability can be pre-calculated for the assumed transmit power and for any given density of transmit mobiles (typically it will be stated in terms of a simple equation where the input is the mobile density). Then for each pixel in the measurement square the number of mobiles can be added up and the equation used to derive the interference levels. Compliance can then be assessed across the measurement square.

These procedures can be readily automated using modelling tools and macros such that it is a simple process to derive compliance information in any situation.

Changing licence terms

If a spectrum user wishes to change the technology that they are going to deploy then the in-band, out-of-band or geographical limits might become inappropriate. The solution to this is for neighbours both in geography and spectrum to mutually agree changed limits. Practically, it seems likely that if, for example, a spectrum user wanted to increase its out-of-band emissions, causing increased interference to a neighbour, it might make some payment to the neighbour to compensate them for the loss of value, or accept a similar increase in interference from the neighbour into its bands.

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[12] In doing so, there is an argument that the licence terms are no longer technology and service neutral. There is a balance here between terms that are generic and those that are optimal. If the initial usage can be predicted with reasonable certainty it seems better to optimise the licence terms for that usage prior to licence award. Then the winners of the licences need not enter into negotiation to optimise their licence conditions after the award. If there is less certainty in predicting the award then more generic limits could be adopted. In either case, because the conditions can be modified by negotiation they enable a change in technology and usage.

The indicative interference level

One of the benefits of interference restrictions is that licence holders can determine the maximum interference level that they would expect to experience by simply adding the allowed PFD limits of their neighbours. This is a very powerful feature which enables a number of advantages:

- Licence holders can use this as their “noise floor” in their network design process, optimally designing their network to cope with the interference they will receive in reality.

- They can use this as a level to trigger investigation into potential interference. Compared to the current approach whereby users are protected from “harmful interference” but what this might be is not quantified, this provides much enhanced utility and protection to licence holders.

- It can be used as part of the process of specifying receiver parameters by licence holders or standards bodies such that receivers have optimal levels of out-of-band signal rejection and are not subsequently interfered with by a change of use by a neighbour (as can happen today).

- If neighbouring bands are reclaimed by the regulator and auctioned it is clear what the licence parameters for that band should be in order that neighbours do not see an overall change in interference.

The indicative interference level is a significant advance in spectrum management and usage, providing certainty around interference levels for the first time.

Spectrum usage rights (SURs)

The following chapters discuss a particular implementation of interference restrictions known as SURs.

8. Specifying the PFD limits[13]

Introduction

In the previous section we mentioned the three PFD limits that need to be specified. In this section we consider their specification in somewhat more detail. First it is worth discussing the statistical nature of propagation and the resulting impact that this has on the licence terms.

Because of the nature of propagation the signal strength from one or more transmitters can vary depending on where it is measured. It can also vary over time even if measured in the same place.

Place. Generally, the closer a measurement point is to a transmitter, the stronger the signal will be. The signal will also vary due to blocking, reflection, refraction and other propagation phenomena. As a result, the interference levels, when considered across a large area will vary significantly from place to place. Hence, conformance to a PFD level cannot be verified by making a single measurement. Instead, a number of measurements must be made and some statistic drawn from them. A typical approach is to require a certain percentage of the measurements to be below a given level – for example at least 90% of the measurements must be below -50dBw/m^2/MHz. The actual number of measurements is related to the percentage selected – as percentages become progressively higher more measurements are required to achieve a given level of statistical certainty.

Time. Signal levels can also vary over time. This could be caused by moving objects, such as vehicles, temporarily interrupting the signal path. Alternatively, it could be caused by changing atmospheric conditions leading to propagation phenomena such as “ducting” where signals can travel over great distances at certain times. Hence, it is necessary to make measurements for an appropriate time period and take the average. Most variations can be removed over a relatively short time period – for example a few minutes would be sufficient to average the variations caused by moving vehicles. However, ducting and other phenomena can cause variations with periods of days or longer and as a result present real challenges to the measurement methodology. We will return to this issue when we discuss whether measurement or modelling is more appropriate in Chapter 10.

Another issue of importance is the height at which measurements are made. Typically, signal strength increases with increasing receiver height so it is important to specify a particular height. The most appropriate height is that at which the interference will typically be received. So, if neighbours have deployed, or are expected to deploy, a mobile downlink then the height specified would be that of a typical mobile – say 1.5m above ground level. For a TV downlink the height might be 10m, corresponding to a rooftop antenna while for a mobile uplink the height might be perhaps 20m, corresponding to a typical base station height. Getting the height “right” is less important than being consistent. For example, an operator who knows the interference that his neighbour is allowed to cause at 20m could make a good estimate of the interference likely to occur at 10m using modelling, measurement or other approaches. However, if an operator has planned their network on the basis of interference at 20m and then is told they must now conform to a 10m limit they may find that their network needs replanning.

In some cases, more than one height may be needed. For example, time division duplex (TDD) systems transmit and receive on the same frequency. Interference could occur both at the base station and the mobile. So a neighbour to a TDD system might have two PFD limits

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[13] This section is based predominantly on Section 4 of the SUR Guide.

– one at (say) 20m and the other at 1.5m. They would need to ensure that they conformed to both.

Geographical interference

In this instance, we wish to protect a licensee's receiver separated geographically from the transmitters of a co-channel licensee. The geographical interference limit is defined as:

> The aggregate PFD at a height H above ground level should not exceed X dBW/m^2/MHz at more than Z% of locations at [definition of boundary[14]].

Interference caused by out-of-band emissions

In this instance, the aim is to protect a victim receiver possibly in the same geographical area from out-of-band emissions from another licensee operating in a neighbouring frequency band. The out-of-band emission limit is defined as:

> The aggregate out-of-band PFD at a height H above ground level should not exceed X dBW/m^2/MHz at more than Z% of locations in a test area.

Defining the PFD limit at a single location is not appropriate, as near a transmitter any PFD limit which results in a reasonable level of interference can be expected to be exceeded. Therefore the PFD limit is defined as a distribution across a range of locations, as shown in Figure 8-1.

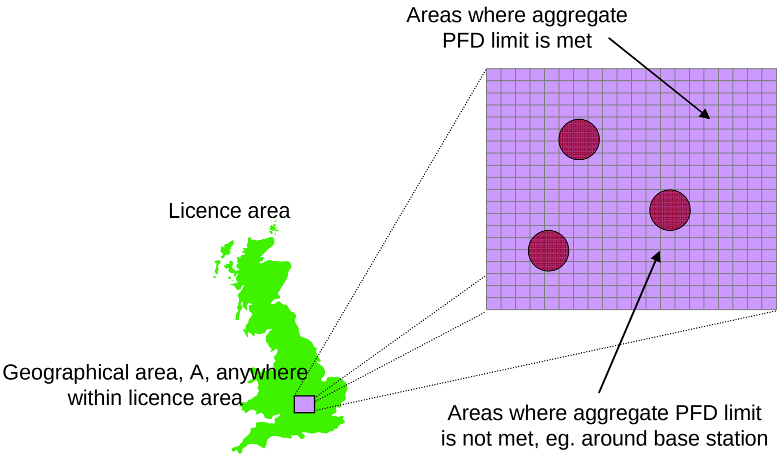

Figure 8-1: Illustration of locations where an out-of-band PFD limit may be exceeded.

PFD restrictions also prevent a licensee from using isolated transmitters operating at relatively high power levels in most practical situations, but if this remains a concern to neighbouring licensees additional forms of restrictions such as an EIRP limit can be included in a licence.

Interference caused by in-band emissions

In this instance, we wish to protect a victim receiver from interference received out of its band of operation, caused by in-band emissions from another licensee. To control this type of interference, an in-band emission limit is defined as:

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[14] The boundary is likely to be the locus of points separating the operational area of one or more co-channel licensees. For compliance purposes, the geographical interference limit may be assessed for only a segment of this boundary.

> The aggregate in-band PFD at a height H above ground level should not exceed X dBW/m^2/MHz at more than Z% of locations in a test area.

The arguments for this approach and the benefits offered as the same as for the out-of-band emissions.

Intermodulation, overload and other spurious emissions

These aspects of interference generally only become an issue with relatively high power transmitters and/or transmission/reception equipment in relatively close proximity.

Intermodulation products (IPs) are generated from multiple signals by non-linearities in the transmit chain, the receiver, or corroded / unclean metal junctions. While IP emissions from a transmitter will largely be controlled by an out-of-band / spurious emission mask, problems may arise when signals from more than one transmitter interact.

Overload occurs when a strong out-of-band signal, which may otherwise be satisfactorily filtered out by the rest of the receive chain, overloads the receiver causing distortion. The degree of degradation due to overload depends on the performance of the receiver front end and the possible implementation of input filtering.

Whereas out-of-band emissions discussed earlier occur immediately outside the necessary bandwidth of the transmission and result from the modulation process, spurious emissions can occur over a much wider frequency range. Spurious emissions include harmonics, parasitic emissions, IPs and frequency conversion products. Receivers can also generate spurious emissions although these are typically at very low power levels.

Control of spurious emissions

Intermodulation products and overload are to some extent controlled by the out-of-band emission limits applying to the transmitter as discussed above. In general, they will not cause a problem and hence complex regulatory mechanisms to address them will be disproportionate.

Where intermodulation is found to occur as a result of the interaction of two transmitters, it should be the responsibility of the licensee who deployed its transmitter most recently to resolve it. This will be clear in most cases from data such as mast rental contracts.

The test area

As mentioned in the definitions above, the interference must be measured over an area termed the “test area”. Determining the size of the test area is a balance - as has been discussed in previous sections. By way of reminder, if the test area is too large, it is possible for a licensee to deploy a very high power transmitter or a network of transmitters within part of the area and still be within its PFD limits when averaged across the whole area. For example, if the test area was all of Southern England then a very high density deployment in London could be averaged out by a lower density deployment in rural areas. Conversely, if the test area is too small, e.g. less than, say, two cells, there is a risk that the area may cover part of a cell such that only areas close to the transmitters are included. Another way of looking at this is that if the test area is moved just a little to the left or the right it might include more or less of the coverage area just around one of the base stations and so a significantly different result would be obtained. This would make derivation of a consistent and representative level difficult. However, if there were 10 or more cells in the test area then moving it slightly would have less impact because each base station makes less difference and on average moving the test area in a way that adds more of the coverage of one base station will tend to reduce the coverage from another.

A further complication is that cell sizes will vary in different geographical areas and may also change over time as an operator splits cells to enhance network capacity so it is not possible to specify the test area directly in terms of km^2.

Many approaches could be considered to this problem. One is for the test area to be defined as a square area including at least ten transmitters. The square would typically be smaller in urban areas where cells were closer together and larger in rural areas. However, if the location of the centre of the square is not constrained in some manner it would be difficult for an operator to be sure they were conforming to their limit. This is because they would, in principle, need to test the interference caused for every possible location of the square, which might, perhaps mean moving the square metre by metre across the country.

A solution to this is to “snap to grid” the square, for example by requiring the bottom left corner to be at the intersection of 1km grid squares. The test area can then be expanded from $1km^2$ until it covers 10 or more transmitters. For simplicity this might be done in steps such as 1 km^2, 4 km^2, 25 km^2, 100 km^2, 400 km^2, 2,500 km^2 or 10,000 km^2.

It is sensible to exclude those parts of the coverage area that are over a water feature (e.g. sea, lake or river) since the interference caused in these areas is generally not of concern and could unduly bias the other measurements.

So, in order to ensure that their proposed network deployment conformed to PFD limits an operator would need to use a piece of software that:

- Moved across all the 1km grid square intersection points inside their coverage area.
- At each intersection point expanded a square in steps until it included at least 10 transmitters.
- Determined the statistics of the PFD levels for that square.

Such software can be obtained, either from supplies of propagation systems or by developing a small macro to run alongside a propagation tool.

There are some services for which this approach is not appropriate. For satellite services there are no ground transmitters. However, coverage across large areas is fairly uniform. Hence, the PFD limit may be set at a few specific locations rather than for a test area. For radar services even areas as large as 10,000 km^2 may not necessarily include at least ten transmitters. In these circumstances, the appropriate test area will need to be determined on a case by case basis.

Summary

To control emissions into neighbouring geographical areas, the following is used:

> The aggregate PFD at a height H above ground level should not exceed X $dBW/m^2/MHz$ at more than Z% of locations at [definition of boundary].

To control emissions outside of the licensee’s frequency band (that appear as in-band interference for a neighbour), the following is used:

> The aggregate out-of-band PFD at a height H above ground level should not exceed X $dBW/m^2/MHz$ at more than Z% of locations in a test area.

To control emissions inside the licensee's frequency band (that may cause interference to neighbouring users in frequency due to imperfect receiver filters), the same measure is used:

> The aggregate in-band PFD at a height H above ground level should not exceed X dBW/m^2/MHz at more than Z% of locations in a test area.

If intermodulation occurs as a result of the interaction of two transmitters, it is the responsibility of the party having most recently deployed a transmitter to resolve the problem.

An SUR licence is expected to include in-band, out-of-band and geographical interference limits. If required by stakeholders, other forms of restrictions (e.g. EIRP limit or transmitter density limit) can be included in an SUR licence to meet particular objectives such as facilitating coordination.

In the next section, we describe the process used change SUR parameters.

9. Changing the use of the spectrum[15]

Introduction

As mentioned previously, one of the benefits of SURs is the ability to change the use that the spectrum is put to so long as the overall interference limits are not increased. This section provides an overview of the change of use process including the procedure to be followed if a change in use does require a change to the licence terms.

The change of use process

A high level summary of the change of use process for an SUR licensee is given in Figure 9-1.

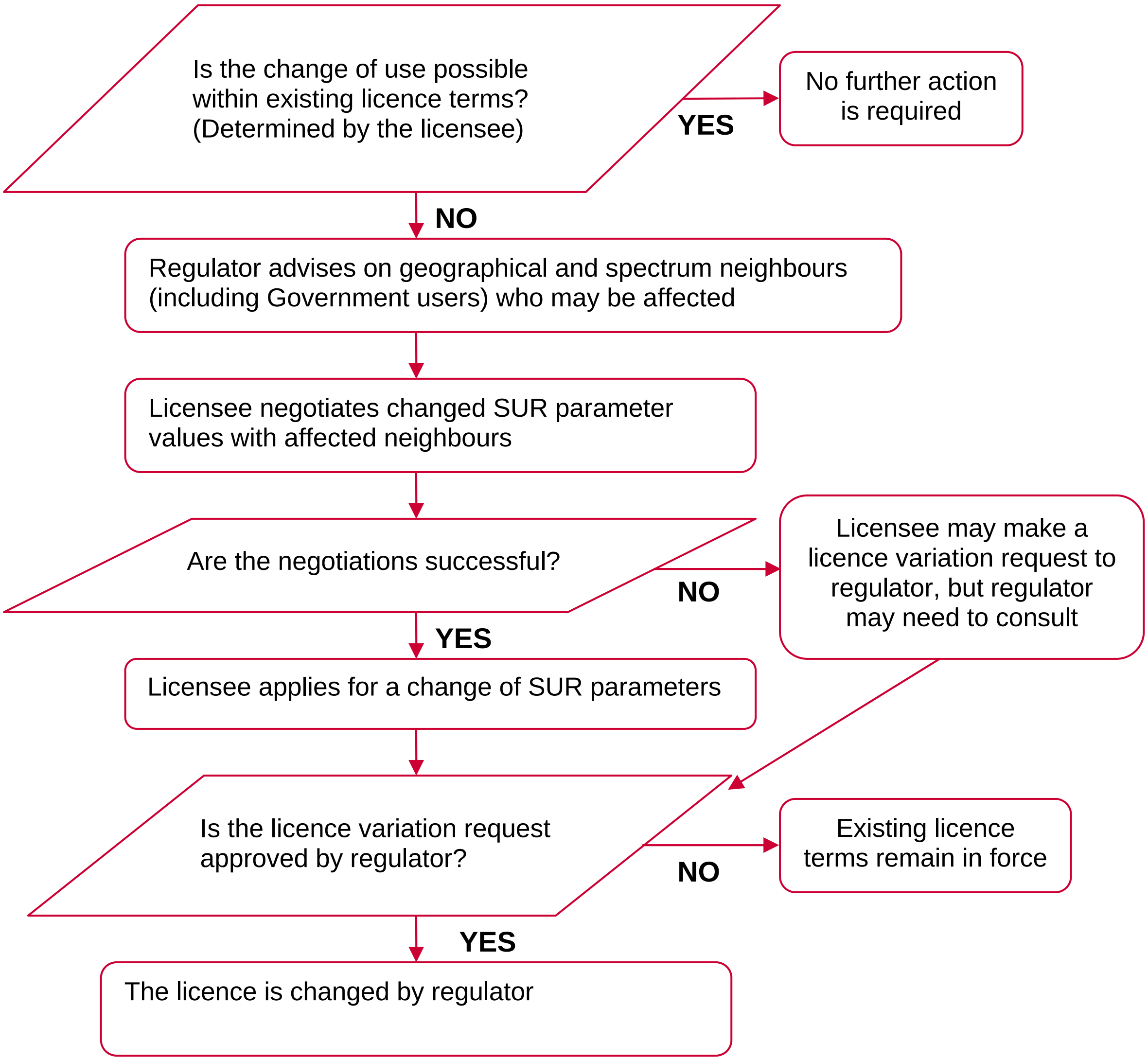

Figure 9-1: Elements of the change of use process based on negotiations with affected neighbours.

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[15] This section is based predominantly on Section 5 of the SUR Guide.

Firstly, the licensee wishing to change its usage should determine whether it can be accommodated within its existing SUR parameters. In many cases this might be possible, but if it cannot, the licensee needs to determine who may be affected by the change of use and enter into negotiations with the identified licensees to agree necessary changes to the SUR parameter values, possibly through compensation for any degradation suffered as a result. It is generally preferable for the regulator to determine who might be affected rather than the licence holder since it is in the interests of the licence holder to minimise the number of parties with which they have to negotiate and so they might be inclined not to undertake such identification thoroughly.

The regulator might also need to advise on any Government users of spectrum who might be affected and any international co-ordination constraints and potentially assist in any negotiations associated with these.

If the agreement of all affected parties can be obtained then the required changes to the SUR parameter values can be requested. The remaining stages of this process are discussed in further detail in the sub-sections below.

Negotiating change of use

Once the affected neighbours have been determined, then the licensee wishing to change its SURs will need to negotiate appropriate terms with these neighbours.

Most cases will be straightforward but there may be issues with certain users of spectrum. These are discussed below.

Licence exempt users. Licence exempt applications are currently protected from harmful interference from neighbouring bands, though there is no protection from other users within the band (assuming they are operating legally). When SURs are established for licences neighbouring licence-exempt bands, the regulator will set the amount of interference allowed into the licence-exempt band. Since there is no single holder of the right to protection for licence exempt applications operating in a band then there are likely to be many unidentifiable users who in effect jointly possess the right to interference protection. As a result, it will generally not be possible to negotiate changes to this protection.

Vacant spectrum and guard bands. If a licensee wishes to make a change of use that can increase the amount of interference experienced in vacant parts of the spectrum the regulator needs to act on behalf of possible future users of the vacant bands and act in a manner that meets the best interest of all parties.

Government users. In most countries the regulator typically manages the interface between government and commercial users, for example by negotiating increased sharing of government spectrum and protection of commercial users' interests in the context of changes in government spectrum use (and vice versa).

International users. In principle, licensees are free to negotiate with other spectrum users across international boundaries.

Registration of change of use

If negotiations conclude satisfactorily, then the licensee wishing to change its use and all other affected licensees will need to apply to the regulator for licence variations. If the changes are accepted a licence variation will be issued.

It is generally best that the regulator does not have a role in approving the technical aspects of the licence variations as such a role would not put sufficient responsibility on the parties concerned to address potential interference problems in negotiations.

Modifying PFD limits for different regions

At present licences are generally provided where in-band and out-of-band PFD limits are constant throughout a licensee's operational area. Licensees who want a higher PFD limit in a particular part of their licence area (for example a higher level in urban areas and a lower level in rural areas) can do so by submitting a licence variation request to the regulator.

10. Measurement or modelling?[16]

The need to verify

Obviously a licence term is of no value unless it is possible for all interested parties to determine whether it is being met. These include the licence holder who would wish to ensure that they were within the terms of their licence before deploying a network, their neighbours who wish to ensure that they are not being subjected to excessive interference and the regulator who might need to take appropriate action. Ideally, verification should be simple and should always lead to the same result, regardless of who performs it.

Verifying compliance to SUR licences

There are two ways in which compliance to an SUR licence could be verified – measurement or modelling. In a measurement approach equipment capable of measuring signal strength is deployed in a number of locations. In a modelling approach the signal strength is predicted rather than measured using a modelling tool. Both have their strengths:

- Measurement captures what is actually happening. However, it is complex and expensive to perform and may not deliver consistent results.
- Modelling is only a prediction of what is happening and will differ from reality on occasions. However, it is simple and inexpensive to perform and delivers consistent results.

Each of the approaches is discussed in more detail below.

Measurement

A process to make measurements of in-band and out-of-band emissions might be as follows.

1. Measurements are made at a uniform grid of points across an area, A, within the victim licensee’s geographical operating area.
2. The number of measurement points should be statistically significant, depending upon the percentile point to be verified (eg 95%). A high percentile would require more positional measurements to be made for statistical confidence. Typically a minimum of 25 measurement locations would be needed.
3. Measurements that cannot be made on a grid point due to obstruction, for example by a building, should be made at the nearest location to the grid point where measurement is possible.
4. Measurements should be made at the height above ground of the typical receiver used by neighbours.

This approach is workable but suffers from three problems.

The first is the effort required to make these measurements. Making 25 measurements across an area might take a team of two or three field engineers as long as a day. If multiple areas need to be measured then the resource requirements could be significant.

The second is the potential lack of repeatability. Because of the variation in signal strength discussed earlier, it is possible that measurements made in the same location but on, say, successive days, might deliver different results. If the measurements showed on one day

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[16] This section is based predominantly on Section 6 of the SUR Guide.

that the licence holder slightly exceeded their limit, they might show on another that they were just within it. If the measurements were to be used as part of a legal process this variability might cause problems.

The third is the possible need to switch off some networks. For example, if the out of band emissions from operator A's equipment into operator B's spectrum were to be measured it would strictly be necessary to turn off operator B's network (and perhaps that of operator C as well) in order that the signal transmitted by A could be isolated. Turning off, for example, cellular networks can lead to significant loss of revenue and customer frustration. There are methods that can be used to approximate the interference level caused by A without turning off B's equipment but they are somewhat less accurate.

A further issue for operators is the margin they must leave in the design stage. When they are designing their network they will typically use a modelling tool to determine whether the network is likely to be within the PFD limits. However, there will be some difference between the tool and reality and hence the operator will need to leave some margin to account for this. Hence, they will typically be unable to take up all of their spectrum rights.

It is also problematic to cope with longer-term variations in propagation such as ducting when making measurements. Some ducting phenomena only occur a few times a year. Strictly then, it would be necessary to make measurements over extended time periods to ensure an appropriate average. This is generally impractical.

Modelling

A process to undertake modelling might proceed as follows (a more detailed description of this is provided in the next section):

1. To verify compliance to an in-band PFD limit due to a broadcasting or mobile downlink type of service (excluding Time Division Duplex), information such as transmitter locations and transmit powers is requested from investigated licensees. A simulation is then run over a test area, in a location chosen by the licensee who has claimed they are suffering interference (the "victim"). Only the neighbouring licensee's transmitters in the test area will be considered in the modelling. At each of the test points distributed uniformly across the test area, an aggregate PFD value is calculated at the relevant height(s).
2. To verify compliance to an out-of-band PFD limit, the out-of-band PFD can be derived from the in-band PFD. Exactly how this will be done will be specified in the licence and the difference applied to the result obtained above.
3. To verify compliance to a geographical PFD limit, the 'victim' licensee highlights a reference point on the geographical boundary where they believe that interference is occurring. The segment(s) of the geographical boundary that occurs within a radius R[17] from the reference point is then used for assessing compliance.
4. The aggregate PFD is determined at test points which can be distributed, for example, on the terrain data resolution used. The test points are expected to be located along the relevant segment(s) of the boundary.

In essence, a representation of the network is made on a computer and the signal strength from each transmitting element is predicted. Modelling overcomes all the difficulties outlined above but leads to other problems.

Firstly, some situations are very difficult to model, in particular transmissions from mobiles. We discuss in Chapter 11 how this might be done.

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[17] The radius R will be specified in the licence.

Secondly, modelling is only an approximate representation of reality. In some cases there will be errors between the model and reality and as a result operators may experience more interference than the model predicts. These actual levels may even be higher than the allowed PFD limits but an operator will be unable to take action against their neighbour if they are within the limits according to the model. This is a key point. In order to provide legal certainty for licence holders deploying networks, if a modelling approach is adopted then if the interference measured in reality is higher their neighbours will have no recourse to complain. Effectively, a set of operators in a band using interference restrictions with modelling have foregone the right to resolution of interference issues that occur in practice but not according to the model. In compensation they have certainty that if they deploy a network that meets their licence conditions according to the model that they will not subsequently have to modify it if interference occurs in reality. Of course, if the model is a good representation of reality then the this case will not occur.

The need for accuracy

Interference restrictions (and SURs as a specific instance of them) enable licence holders to be sure that they will not suffer interference from their neighbours. Clearly the more accurately the licence terms and verification methods reflect the actual interference caused, the better they will work. However, it is important to understand that if they are somewhat inaccurate they can still be a useful tool.

The effect of any inaccuracy is that the interference level set in the licence (the PFD level that must not be exceeded at more than a certain percentage of locations) may be exceeded in practice. For example, instead of the set level being exceeded at no more than 5% of locations, it might turn out that it is exceeded at 7% of locations, or alternatively if the error is the other way, at no more than 3% of locations. The interference level is a tool used by neighbours in designing their networks such that they function correctly regardless of any change of use. Hence, in the worst case neighbours may find higher interference levels than the licence terms suggest which could cause problematic interference to their network. Because any model can be used in any band, licence holders are able to select a model that meets their requirements for accuracy.

It is worth recalling that if interference restrictions were not used, perhaps because of concerns over their accuracy, the alternative would be transmitter restrictions. As we have discussed in earlier sections, even the best of these is much more inaccurate at predicting interference levels than any of the approaches to interference restrictions.

A preference for modelling

Either measurement or modelling can be used to verify SURs. The approach can be varied from band to band according to the circumstances and requirements of the licence holders. It can even, in principle, be changed during the lifetime of the licence if the licence holders wish. Hence, no “final” decision need be made.

After extensive discussion with a wide range of stakeholders, it appears that there is a general preference for modelling because of its simplicity, repeatability and low cost. As a result, the remainder of this document assumes the use of modelling to confirm compliance.

11. Verification by modelling in detail[18]

Introduction

As mentioned previously, an SUR is of no value unless it can be determined whether the licence holder remains within their limits. We term this process verification.

Verification by modelling requires a clearly defined procedure to be set in place such that all parties can perform the modelling themselves and derive an identical answer. This means, for example, that random variables cannot be used as are often done in Monte-Carlo type modelling exercises because this would result in differing results each time the model was run.

There are many trade-offs to be made between accuracy and simplicity of modelling. For example, one key area is whether to model indoor deployments. This is very complex to do, but may result in inaccuracies if not attempted.

It is worth stressing that while the discussion in this chapter may be complex, the results of the discussion are then encoded as a macro or as part of a software tool. Verifying compliance then becomes a very simple process of initiating the macro ("pressing the button" on a software tool). Hence, in the same manner that 3G cellular systems are complex but this complexity is completely hidden from the user, once SURs are implemented within software tools none of the complexity will be apparent to the licence holder.

Types of modelling needed

Different modelling approaches are needed according to whether the transmitters are base stations or mobiles since the location of mobiles cannot be known with certainty. For both of these types, different methods may be needed according to whether the neighbouring bands are themselves uplinks or downlinks. This leads potentially to four different types of modelling:

- From one downlink to another adjacent downlink.
- From one uplink to another adjacent uplink.
- From one downlink to an adjacent uplink.
- From one uplink to an adjacent downlink.

Combinations of these cases can cover situations such as the use of Time Division Duplex (TDD) technology. We provide a brief overview of the approach adopted first and then discuss the issues in more detail in the remainder of this chapter.

Not all of these may necessarily be needed. For example, it might be decided only to model downlinks and to use other licence restrictions to prevent changes to an uplink.

For the downlink to downlink case information such as transmitter location and transmit power is requested from investigated licensees. A simulation is then run over a test area, in a location chosen by the 'victim' licensee. Only the neighbouring licensee's transmitters in the test area will be considered in the modelling. At each of the test points distributed uniformly across the test area, an aggregate PFD value is calculated based on the sum of

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[18] This section is based predominantly on Section 7 of the SUR Guide.

the predicted interference from each of the neighbour’s transmitters at the relevant height which will typically be that of a mobile (eg around 1.5m). The PFD value is based on the transmit power specified, the antenna radiation pattern and the propagation loss as predicted by the propagation model specified within the licence.

For the uplink to uplink case the approach is to determine for each cell in the test area a representative number of mobiles in the cell. The approximate coverage area of the cell is then determined and mobiles distributed evenly across the cell. Each mobile is assigned a transmit power based on their distance from the base station. The total interference from all mobiles to each test point in the measurement area can then be determined using the same propagation model as adopted for the downlink to downlink interference case.

For the downlink to uplink case the approach is to sum the interference from each of an operator’s base stations at each test point across the measurement area. Both the transmitter and receiver are assumed to be at heights typical for base stations.

For the uplink to downlink case the approach is to model the interference occurring at each test point within the test area. This modelling is based on assessing the density and average power of mobiles within the test point and determining the interference caused to multiple points throughout the test point using transmitter and receiver heights typical for mobiles. In practice, a simple formula can be provided such that if the density and average powers are known the interference can be quickly determined without needed to perform modelling.

We now look at each of these cases in more detail, starting by setting out the terminology used.

Terminology

The *test area* is an area covering at least 10 transmitters. Its size is determined based on how large it needs to be in any given location in order to enclose at least 10 transmitters, as set out in Chapter 6. Generally, it might be expected to cover many square kilometres.

Test points are smaller locations within the test area. Their size will be set out in the licence and will typically depend on factors such as the resolution of the underlying mapping data. For example, a typical size for a test point might be 50m x 50m. In any test area there may be hundreds or thousands of test points.

Geographical interference

To verify compliance to a geographical PFD limit, the ‘victim’ licensee highlights a reference point on the geographical boundary where they believe that interference is occurring. The segment(s) of the geographical boundary that occurs within a given radius from the reference point is then used for assessing compliance.

The aggregate PFD is determined at test points which can be distributed, for example, on the terrain data resolution used. The test points are located along the relevant segment(s) of the boundary.

The actual transmitters of the investigated licensee to be included in the modelling will be specified in the licence terms. In the extreme, all of its transmitters causing signal levels at the boundary higher than the UWB (ultra-wideband) mask (as defined in the European Commission Decision 2007/131/EC) could be considered in the modelling.

Downlink to downlink

To verify compliance to an in-band PFD limit due to a downlink type of service (excluding Time Division Duplex), information such as transmitter location and transmit power is requested from investigated licensees. A simulation is then run over a test area, in a location chosen by the ‘victim’ licensee. Only the neighbouring licensee’s transmitters in the test area need be considered in the modelling. At each of the test points distributed uniformly across the test area, an aggregate PFD value is calculated based on the sum of the predicted interference from each of the neighbour’s transmitters at the relevant height which will typically be that of a mobile (eg around 1.5m). The PFD value is based on the transmit power specified, the antenna radiation pattern and the propagation loss as predicted by the propagation model specified within the licence.

Uplink to uplink

To verify compliance to an in-band PFD limit due to a mobile uplink type of service (excluding Time Division Duplex), the first step is to approximate the number of mobiles and their transmit power. Generally, it is either not possible, or extremely difficult to determine the actual number of mobiles as this varies continuously depending on factors such as mobile location, services used (eg voice or data) and overall interference levels. Hence, we estimate at the time that the licence is written, what a typical maximum[19] number of mobiles per channel would be. For example, for a 3G system we would estimate the maximum number of voice calls that can typically be supported in a cell on a 5MHz carrier. This would be written into the licence as an assumption and no attempt would be subsequently made to verify it in practice. If, through technological progress, the number actually supported on the network increased over time, the regulator would not automatically change the assumed number provided in the licence but might consult with all affected parties to understand whether they wished to see any change.

In some cases it may be necessary to take into account frequency reuse – ie the fact that not all frequencies are in use in all cells. This can be done by dividing the capacity per channel by an assumed frequency reuse factor. The simplification can then be made of assuming all frequencies are in use in all cells.

The next step is to determine the coverage area of each of the cells in the test area. At each test point the signal strength from each cell is predicted. If the path loss from at least one cell is less than a maximum set in the licence then the cell providing the strongest signal is taken to be the “serving cell” for that test point, otherwise the test point is considered not to have coverage. The coverage area of a cell is then the sum of all the test points in the test area where it is the serving cell.

The mobile terminals served by a cell are then evenly distributed within its coverage area. This is done by dividing the number of test points where the cell is the serving cell by the number of mobiles (eg 650 test points divided by 60 mobiles = 10.8) and taking the closest integer value termed *n* (11 in this case). Then working across the test area in a conventional raster manner[20] a mobile is placed at the centre of every n^{th} test point. If $n<1$ then more than one mobile is placed at the centre of the test point as needed. For example, if there were 60 test points and 90 mobiles then alternately one and then two mobiles would be placed at the centre of each cell. Where multiple mobiles are placed they are assumed to be collocated.

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[19] This is the maximum number of users that can be supported assuming a fully loaded network across the test area ie all cells in this area are at optimal load points to maximise capacity across the area.

[20] Starting in the top left corner, moving across the top row the returning to the left hand side of the second row and moving across that, etc.

Each mobile is assigned a transmit power level based on the predicted path loss to the serving cell. In the licence the assumed maximum transmit power and maximum path loss will be provided. The transmit power is then reduced by the difference between the actual path loss and the maximum path loss. For example, if the maximum transmit power was 25dBm at a path loss of 150dB then if the path loss at a test point was 130dB a mobile transmit power of 5dBm would be used.

At each test point within the test area, the aggregate PFD at the height of the base station due to the mobile terminals is calculated using an appropriate propagation model as stated in the licence. Due to reciprocity, this model can typically be the same as the one used for the downlink to downlink interference case. If there is one or more mobiles within the test point under consideration (so that they would be very close the a base station in practice) then the distance used in the propagation model for this mobile is set to half the width of the test point resolution (eg if the test point is 50x50m resolution then the distance is set to 25m).

In practice, it is unlikely to be necessary to model the propagation from each mobile since the received signal level will be predominantly composed of the signal from a small number of nearby mobiles. Hence, approximations such as only considering the five closest mobiles could be adopted if desired.

To verify compliance to an out-of-band PFD limit, the out-of-band PFD can be derived from the in-band PFD according to a method specified in the licence. In some cases, if appropriate, this can be based on the Adjacent Channel Leakage Ratio (ACLR) or the transmitter spectrum mask or other attenuation mask as specified in the relevant standards or alternatively it can be based on actual measurements of a few transmitters.

Mixed downlink and uplink

There may be situations when it is necessary to consider the interference caused by neighbours operating links of different directions. For example, one operator may be using a band as a downlink while their neighbour is using their band as an uplink. Or the neighbour might be using time division duplex (TDD), effectively using their band as both an uplink and a downlink simultaneously. This section sets out proposals to model these situations to ensure compliance with SUR levels.

Note that in general significant interference can occur if uplinks and downlinks are operated close to each other in frequency terms. When deriving SURs appropriate PFD levels will be set to reflect this. For example, the PFD that an uplink user is allowed to generate into the receiver of a downlink user might be set to very low levels. As a result of this, the uplink user may create a guard band or take other action to enable them to deliver an economic service while still meeting their PFD limits.

We firstly consider the two cases of uplinks interfering with downlinks and downlinks interfering with uplinks. We then show how these, coupled with the downlink to downlink and uplink to uplink modelling processes can be used for the case of TDD.

Uplink to downlink

Imagine the situation where two adjacent operators, OA and OB, are both using their bands for downlink transmissions with given SUR levels. OB now decides to change their downlink to an uplink[21]. In doing so they must respect their SUR levels, ensuring that OA suffers no more interference than would be the case if their link was used as a downlink[22]. The interference mechanism relevant to operator OA is now the interference from OB's transmitting mobiles into OA's receiving mobiles.

In outline, the way to model this interference is to determine a representative distribution of OB's mobiles, assign a transmit power to each mobile and then model the interference to a set of locations. Because mobile density can vary from location to location, this process needs to be performed at multiple locations across a test area. This process is now described in more detail.

The process starts in an identical fashion to the general uplink to uplink case described above by establishing a test area. Operator OB is then requested to provide details of all their base stations within this area. As with the uplink to uplink interference process, a representative number of mobiles will be specified in the licence[23]. Then, as with the uplink to uplink case, the mobiles are distributed evenly across the coverage area of the cell and assigned a transmit power based on the modelled path loss. It is at this point that the process departs from the uplink case.

Processing then proceeds on a 1km x 1km tile basis. For each tile the number of mobiles within that tile and the average power of those mobiles are assessed. At the time that the licence is issued the regulator can supply a formula to convert mobile numbers and power levels to PFD numbers. This can simply be used to derive the PFD limits for that tile. This completes the process that would be followed by licence holders. Some additional notes are provided below as to the reasoning that was used to develop this approach.

The first point of note is that taking the average mobile power within a given tile is a simplification. In practice, mobile power levels will vary, although the variation within a 1km grid square will be less than across larger areas. Modelling suggests that the error associated with taking the average mobile power compared to modelling individual mobiles with different power levels is around 4dB. However, taking average power levels allows the licence holder to make use of the pre-defined formula rather than having to simulate each grid square themselves.

The second point is that this approach does not model the "clustering" of subscribers that can sometimes occur in a cell – for example if there is a sports venue within the cell then on a few occasions a week a high mobile density might be experienced in that area. Modelling the effect of such clustering suggests that if around 80% of the subscribers cluster in 20% of the cell that the PFD limits differ by around 1dB from the case of an even distribution. With a more extreme clustering of 90% of subscribers in 10% of the cell the difference only rises to 2dB. Given that clustering will not occur in all cells, and where it does occur it may only be for limited periods of time, it does not seem appropriate to increase the complexity of the modelling in order to accommodate it.

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[21] The analysis that follows also applies to an auction where there is a boundary between uplink and downlink usage.

[22] Note that in practice meeting these SUR requirements will impose severe operational restrictions on using the band as an uplink, and an operator would likely seek agreement with their neighbour for modified SURs or choose to set aside some of their band as a guard band.

[23] If this has not been specified, for example, because the licence was initially intended for downlink usage, then the licence holder OB would firstly need to request that Ofcom add this information to their licence.

It is not necessary for a licence holder to understand the process that follows to determine the equation relating mobile density to PFD levels, but this process is described here in outline for completeness.

The mobiles are firstly distributed evenly across the 1km grid square. A measurement point is then "walked" across the test point in a manner uncorrelated with the mobile distribution process[24]. At a suitable number of evenly spaced points along this walk, the interference from all the mobiles in the grid square is calculated in a manner described shortly. This then gives a distribution of PFD levels. A single value is then taken from this distribution at an agreed level of probability, eg the 95% percentile point. This process is then repeated for different mobile density levels.

The mobile-to-mobile interference is calculated by determining the distance from the measurement point to each mobile in the grid square and then using an appropriate propagation model to determine the path loss. Coupled with the assumed transmit power, the interference can then be found.

For example, such a curve is shown as the solid line for one particular case[25] below. This could readily be approximated by a straight line shown as the dotted line in the figure below and the equation for this line supplied in the licence.

Figure 11-1: Solid line is modelling of PFD limits for various mobile densities with 100mW transmit power at 2.6GHz. Dashed line is best fit straight line to curve with equation $y=-62.7+10.2 \log_{10}$ (mobile density)

Downlink to uplink

Consider the situation where adjacent operators OA and OB are using their bands for uplink. Operator OB now wishes to change their use to downlink. As before, OB must not exceed its SURs and so must not cause any more interference to OA than before it made this change. The interference mechanism of interest is now from the transmission of the base stations of operator OB into the receivers in OA's base stations.

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[24] For example, if the mobiles are distributed on a square grid then the measurement point might be walked diagonally from one corner to another.

[25] This is based on 100mW transmissions at 2.6GHz.

As before a test area A is established. However, now operator OB is requested to provide the locations and transmit power levels of its base stations. At each test point across area A the interference from OB's base stations is established as follows.

The propagation loss from each of OB's base stations to the test point is firstly established. This would use a propagation model suitable for the situation where both ends of the link are generally above the clutter as is normal for base stations. The received signal level at each test point is then determined based on the sum of the transmit power and path loss for each base station. This process is repeated for each test point and a distribution of interference obtained from which the SUR parameters can be verified.

Changing an uplink or downlink to TDD

Now consider the case where operator OA is operating a downlink and operator OB wishes to change their downlink to a TDD link. OB can now potentially cause interference by two mechanisms. The first is downlink-downlink interference and the second is uplink-downlink interference. Both of these can be determined according to the processes set out above and then added together for each test point.

Similarly, in the case where OA is operating an uplink and OB wishes to change from an uplink to TDD then the interference is comprised of uplink-uplink interference and downlink-uplink interference. As before, both of these can be calculated for each test point and added together.

When adding the levels of interference from the downlink and uplink components of the TDD transmission the average TDD downlink-uplink ratio should be used to ensure they are added in the correct proportions. For example, if the ratio is 50:50 then both types of interference are halved (to account for the 50% duty cycle) then summed. At the start of the investigation process operators would be requested to provide a typical duty cycle for their network.

TDD adjacent to TDD

Finally there is the case of SURs for two adjacent TDD users. In this case each operator will be concerned about:

- The interference to the downlink portion of their TDD operation, which comprises downlink-downlink interference and uplink-downlink interference.
- The interference to the uplink portion of their TDD operation, which comprises uplink-uplink interference and downlink-uplink interference.

The modelling approaches set out above are sufficient to cover these cases.

Directional and adaptive antennas

There may be cases where antennas are used that do not illuminate the whole cell or sector but instead seek to direct a narrow beam at a receiver. These may be fixed in their direction and beamwidth, for example as used in fixed link systems, or they may be adaptive, changing direction and beamwidth in accordance with subscriber behaviour.

Directional antennas are also used at the receiver end, for example by rooftop TV antennas. Such an antenna will accentuate the interference received in its direction of pointing but attenuate the interference from other directions. If the interference was evenly distributed around the antenna then the overall effect in terms of interference received by such a directional antenna would be no different from that of an omni-directional antenna. Because the modelling described is not sufficiently detailed to account for direction of pointing of receive antennas it is sensible to make the assumption that the interference is evenly distributed and hence the directionality can be ignored.

When modelling a conventional downlink the operator is requested to provide the transmitter power and also the antenna pattern of the antennas used such that the signal radiated in any direction can be determined. These antennas may actually be directive – for example they may illuminate a sector of a cell.

When modelling an adaptive antenna, the antenna is assumed, over a reasonable period of time, to provide even illumination across the sector of the cell which it is serving. The total power delivered into all the antenna elements is assumed to be radiated into this sector. Hence, an adaptive antenna is modelled as a non-adaptive sector antenna where the power radiated is determined based on the total power delivered to all antenna elements.

For such adaptive antennas the out-of-band power radiated is also determined in the same manner – namely the sum of the out-of-band powers delivered to all antenna elements.

Mobile relay

In this case a mobile network is using some mobiles to relay the signals from others. This might be, for example, mobiles out of coverage of a base station whose signal is relayed through mobiles within the coverage zone to the base station.

For simplicity, it can be assumed that the density of the transmitting mobiles outside of the coverage area is lower than that inside – if this were not the case then there would likely be insufficient relaying capacity from the mobiles at the edge of the network. Because the density is of these mobiles is lower then the transmissions from them are unlikely to affect the overall statistics materially, especially where a relatively high PFD percentage such as 95% is adopted. Therefore, such activity can be ignored for the purposes of SUR calculation.

Mesh networks

An extension of the situation set out above is a pure mesh network where there are no base stations and mobile devices communicate between themselves. It seems unlikely that such networks will be deployed in licensed spectrum. Instead they would be deployed in licence-exempt spectrum where SURs do not apply.

If an operator did decide to deploy such a network it would still need to meet its SUR requirements. In a pure mesh there appears to be no easy way to control the mobile density or transmitted power. Therefore, it appears that an operator could not change from an existing licence to this type of deployment and still be able to demonstrate that they met their SUR requirements.

Indoor transmitters

In some networks some of the base stations are located indoors. For example, cellular operators deploy some cells within airports, shopping malls, etc and might increasingly deploy femtocells within homes.

Modelling indoor cells is particularly difficult because the fabric of the building makes a substantial difference to signal levels. To model them correctly would require detailed building plans for each of the buildings within which the cell was located. Approximations could be used but will tend to be inaccurate.

Fortunately, in most cases the impact of indoor cells on total interference levels is small. This is because the cells themselves are typically relatively low power and because the building fabric will tend to attenuate the signal significantly as it leaves the building. There may be a few special cases where this is not true – for example within an airport each operator may have multiple cells and be concerned about the interference levels that their neighbours are causing.

Because of the complexity of indoor cells and the relatively small amount of interference that they cause, there is little merit in including them within the modelling approach. If neighbours are unduly concerned about particular special cases then they can put forward specific solutions that might work in those situations.

12. Using SURs in practice[26]

Introduction

The section illustrates how an SUR would be used in practice in order to provide further clarity. While it does not present any new information above that in the previous chapters, it does present it in a different manner.

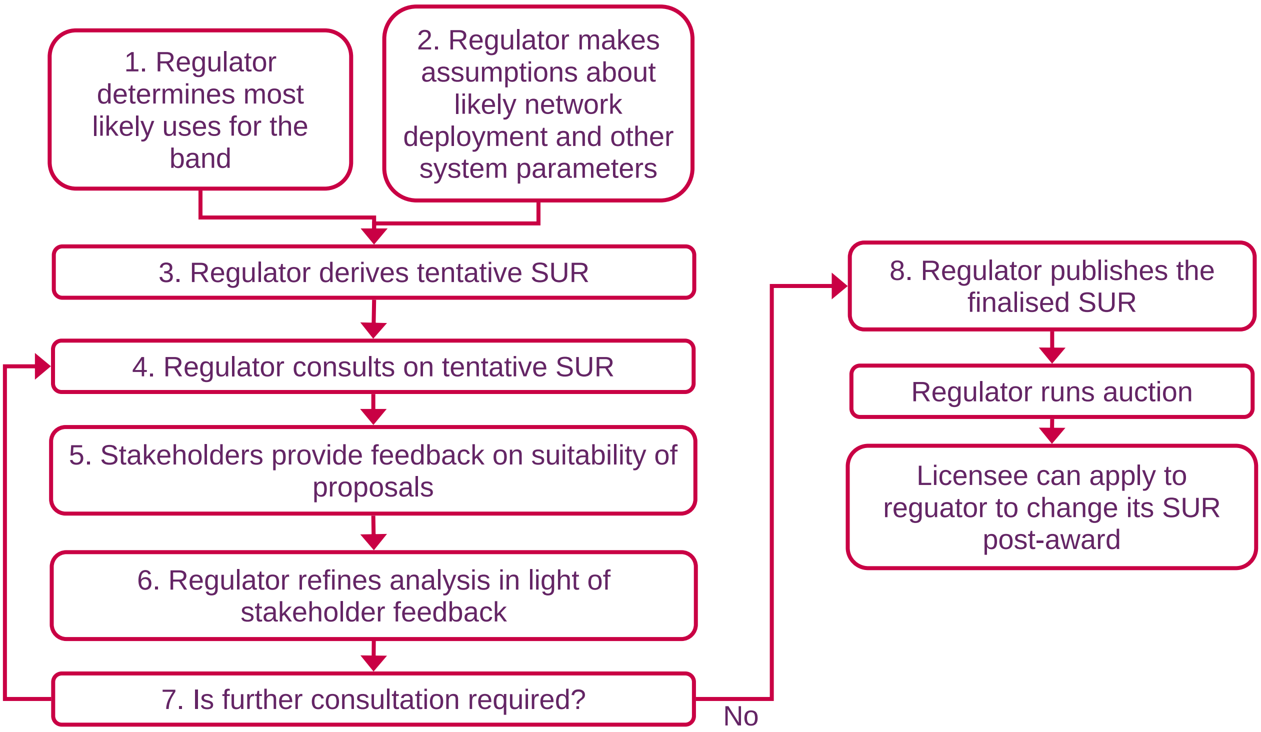
The key stages in an SUR "lifecycle" are:

1. Setting the SUR terms.
2. SURs and coordination.
3. Planning the network.
4. Verifying conformance.
5. Changing the terms.
6. Trading the licence.

Each of these is considered in turn.

Setting the SUR terms

Once a band has been selected for auction and it has been decided that SURs will be used the next stage is to set the actual PFD limits as well as associated details such as the propagation model to be used, the measurement heights to be adopted and so on. Most of this activity is performed, or coordinated, by the regulator. A flowchart summarising the process is provided below.



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[26] This section is based predominantly on Section 8 of the SUR Guide.

Figure 12.1 – Flowchart showing the process for setting SUR parameters

The PFD limits should ideally be set so that they both allow flexible use of the band in such a way that the owner is not restricted as to their deployments while at the same time preventing significant interference to neighbours. Achieving both of these objectives is not always possible and a balance may need to be struck.

Setting the limits for the owner. Firstly the regulator determines the most likely use for the band. It may do this through consultation or study. There may be uncertainty about the most likely use in which case multiple SUR parameter sets might be derived, optimised to each possible different use. The auction process can then be used to determine the most valuable uses and the appropriate SURs attached to each.

Based on the most likely use, assumptions are made as to the technology that will be deployed and the network topography and density. For example, if it is assumed that the band will be used for cellular telephony then 3G technology deployed in the same manner as current 3G networks might be assumed. Appropriate propagation models and modelling approaches are also selected.

The regulator will then try to model the “worst case” part of the network – that is the deployment scenario that generates the greatest PFD values. For a cellular network this is typically in dense urban areas. This deployment is created within a model and the PFD limits that result are determined. The reason for selecting the worst case area is that, were a different area selected, the PFD limits derived would be insufficiently high for the worst case area, restricting the operator’s network deployment. This then gives the PFD values that should allow the band owner flexibility in their deployment.

Setting the limits for the neighbours. There are two cases for neighbours – those that are already using the spectrum and those that will buy the spectrum at auction. For those already using the spectrum one approach is to estimate the levels of interference that would disrupt their service. This is often relatively simple – for example by looking at a typical transmitter-receiver link and understanding the signal-to-interference ratio needed for correct operation the problematic interference levels can be found.

For those neighbours also buying the spectrum generally the assumption will be that they will use the same technology and deployment scenario as others buying the spectrum. Here the interference levels will be those appropriate for two similar neighbouring deployments. Often the designers of the technology, such as the standards body responsible, will have considered this case when specifying the filtering needed for transmitters. The regulator can then simply take the difference in the transmitter mask within the band and out of the band and subtract this from the in-band PFD limits deduced. So, for example, if the transmitter mask allowed 30dBm in band but -10dBm out of band then the difference would be 40dB and the out-of-band PFD levels should be set 40dB below the in-band levels.

Where there are conflicting needs from the owner and the neighbours the regulator will need to determine the most appropriate compromise position, based perhaps on an estimation as to the relative value of the different services.

SURs and coordination

It has long been known that radio services can be packed more closely together in frequency where they are alike and where the operators coordinate their deployments – for example by co-siting base stations – such that the most serious cases of interference are mitigated.

In a “command and control” environment it is possible for the regulator to ensure that neighbours deploy like services with similar technologies and even to engineer coordination between them. For example, this occurs within the TV broadcast spectrum at UHF where international bodies with attendance from the broadcasters, regulators and others plans individual transmitter locations and frequencies such that interference between neighbouring channels does not occur.

With market forces, the regulator cannot ensure like services are deployed in adjacent channels; nor can they either provide or enforce coordination between neighbouring operators. Nevertheless, in many cases, neighbours will choose to coordinate in some manner because in doing so they will be able to increase their utilisation of the spectrum. For example, cellular operators often coordinate over deployment issues either at geographical or frequency boundaries despite the fact that there is no obligation for them to do so.

In general, a regulator setting licensing conditions must assume that coordination will not occur but would ideally allow for a change in conditions if it were to happen. This means that sometimes relatively conservative PFD levels are needed but that through the negotiation and licence change process operators can then modify these limits if they feel this is appropriate.

Planning the network

An operator would typically plan a network using their preferred modelling tool – these are often proprietary or optimised versions of commercial tools. Alongside, or as part of the same tool they would need to implement the propagation model and modelling process agreed as part of the licence. Once they had planned their network using their own tool they would need to run a complete check, for every possible test area as to whether they were exceeding their PFD limits both on the downlink and the uplink, where applicable. If they were then they would need to modify their network plan accordingly and repeat.

The same process would be followed whenever changes were made to the network that were thought to be sufficiently material that the PFD levels might change enough to exceed the limits. However, the process only requires the invocation of a “checking function” on a propagation tool and should be simple and require minimal effort.

In case the operator exceeds the PFD limits in its licence, it will have to consider decreasing the number of subscribers being served in the area of interest or negotiating a higher limit with its neighbours.

Verifying conformance

An operator may, at some point, suspect interference into their network. They may suspect this as a result of decreased network performance, notification of excessive dropped calls or as part of routine maintenance. It would be normal for the operator to perform a few checks to make sure that the fault was not their own before taking the matter further.

If the operator suspects that the fault is being caused by a neighbour they may choose to discuss the matter directly with them and may reach a resolution. Alternatively, they may involve the regulator. In many cases the problem may be relatively simply resolved – for example it may be caused by a jammer or faulty household device. If not, the regulator determines which operators may be at fault and requests from them the necessary network data. The regulator then uses their modelling tool to determine whether the operator is compliant with their licence terms. If they appear to be, but there is still evidence of interference, then the regulator may check that the network data provided is correct, for example by actually measuring the power output of a number of base stations. If these differ from those provided by the operator then the model is re-run using the actual power levels measured. If the modelled results now exceed the licence terms then the operator will be required to make appropriate changes to their network. If not, further investigation may be needed until the cause of the problem is finally understood.

Changing the terms

At some point in the duration of the licence, the operator may wish to change the terms of their licence. This might be because:

- Along with a neighbour they have concluded that modifying the interference levels they can cause each other will allow them to use the spectrum more efficiently.
- They wish to deploy a new technology or service which cannot be accommodated within the existing SUR limits.

To make a change to their terms they need to gain the agreement of all affected parties as advised by the regulator. These will typically be neighbours in frequency and possibly neighbours in geography. Operators beyond the immediate neighbours might also be affected. How they reach this agreement is up to them, but it might, for example, involve making some compensatory payment or accepting a reciprocal change in a neighbour's licence terms.

Once they have this agreement the regulator can change the licence.

13. Summary

Licenses are needed to restrict interference

Without licences significant interference might result between spectrum licence holders. The terms of the licence should be set such as to limit the interference that one user can cause to another while at the same time allowing users the greatest degree of freedom to change their technology, usage or deployment. Transmitter-based licensing restrictions have broadly worked to date but with a change to more flexible spectrum use there is clear evidence that they will not do so in the future.

A key concern is to protect neighbours when a significant change of use occurs. For example, consider two operators A and B who both have deployed a terrestrial broadcast network. Because this broadcasts to directional antennas at rooftop level it has a relatively low average signal strength. Now imagine that B decided to change their network to a mobile TV usage. This requires a much greater signal strength in order to reach mobiles that are at street level and have small non-directional antennas. To achieve this B would typically deploy a much denser network of base stations. The resulting interference that A would experience would rise dramatically – by some 20 – 30dB. This could result in 10% of A’s subscribers or more no longer being able to receive a TV broadcast. A licensing approach used in conjunction with a flexible approach to technology and usage should provide appropriate safeguards for such a situation.

Restrictions can be set either on transmitters or interference levels caused

All the approaches to licensing seek to control the interference caused to neighbours. They do so either by:

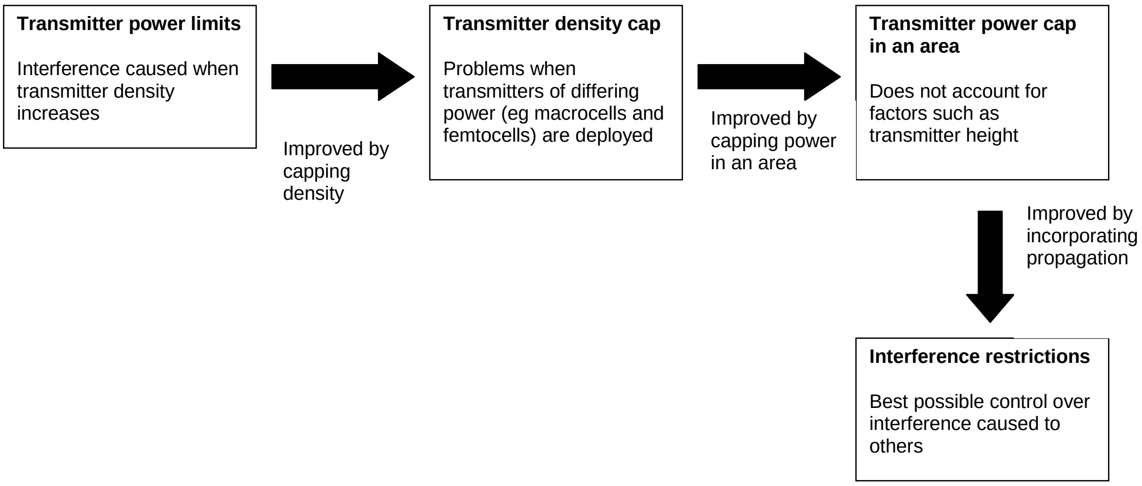
- Placing direct restrictions on the transmitters, resulting in indirect resulting restrictions on the levels of interference experienced by neighbours, or:
- Placing direct restrictions on the levels of interference experienced by neighbours (and as a result, indirectly restricting the transmitters).

We can term these transmitter restrictions and interference restrictions, respectively.

The reason that the approaches are different is because of the indirect linkage between transmitters and interference. There is clearly a linkage in that the interference can only be caused by transmitters and the more power a transmitter emits the higher the interference experienced by a neighbour. However, the linkage is indirect because the interference experienced depends on both the power transmitted and the propagation path between the transmitter and the victim. This propagation path in turn depends on the distance from the transmitter to the victim and the nature of any obstacles between them. So, if a neighbouring receiver is closer to a transmitter it might generally expect to receive more interference. The implication of this is that a licence holder could stay within its transmitter restrictions, such as the maximum power level, but by deploying a denser network of transmitters increase the interference experienced by a neighbour. In this case, the transmitter restriction provides only weak control over the interference experienced by a neighbour.

In outline, transmitter restrictions commence with a spectrum mask, or “block edge mask” (BEM) which sets limits on the power that can be transmitted both within the band owned and outside of it. Enhancements can then be added to provide greater protection against increased transmitter density such as a cap on the density of transmitters per unit area, or better a cap on the total power transmitted by all the transmitters within a unit area. These enhancements go some way towards more directly controlling the interference but add additional complexity.

Transmitter power caps can be further evolved by adding in propagation. They then become interference restrictions which set limits on the amount of interference that can be caused across geographical boundaries, within the band owned and outside of this band. These limits are specified in terms of power flux density (PFD) levels that can only be exceeded in a certain percentage of locations. They are best verified through modelling. The methodology behind this can be somewhat complex but can be automated within a modelling tool such that this complexity is hidden from the licence holder. In fact, the different licensing schemes can be seen as a progression from masks to interference restrictions as shown in the figure below.



Alternatively a licence-exempt of light licensing approach can be adopted where the regulator makes little attempt to directly control interference. This is not considered in detail in this document.

Comparisons

A comparison of the different approaches against some key variables is provided below.

Approach	**Risk that licence holders might suffer interference**	**Ease of use**	**Can be modified if neighbours negotiate**	**Control of holes**
BEM	High	Very simple	No	Size limited but not number
BEM with transmitter density	Moderate	Moderate	Density cap can be relaxed	Size and number limited
Transmitter power per unit area	Moderate	Moderate	Power cap can be relaxed	Size and number limited
Interference restrictions	Low	Complex	Interference level can be changed	Total area limited
Coordination	High unless coordination is effective	Depends on agreement	Depends on agreement	Depends on agreement
Licence-exempt / light licensing	High	Depends on scheme selected, normally simple	Generally not as there are too many neighbours	None

As the table shows, there is generally a trade-off between the level of interference control achieved and the ease of use of the scheme.

Different types of restrictions are appropriate for different cases

Interference control is less of an issue where

- All the users in a band are already using networks that deliver high PFD levels and therefore a change of use of their neighbours to a network causing an even higher PFD level is not plausible. This would be the case typically for cellular networks.
- All the users in a band are using similar networks and there is no likelihood of a change of use.

The first situation might occur in bands used entirely by cellular operators, such as the existing 900MHz, 1.8GHz and 3G bands, and likely in the 2.6GHz band after auction. It is less clear where the second might occur since it would be difficult to be certain that a change of use would not occur over the next 10-20 years that some licences last. In these cases the simpler transmitter licensing approaches might be most appropriate. In other cases it might be preferable and less risky to adopt a receiver restriction or SUR approach.

These conclusions refer to licences that cover substantial areas – perhaps the whole of a country or region. However, there are some applications where users only require a single transmitter or a small number of transmitters. These include private radio systems such as those used by taxi companies and fixed links used to provide a connection between two individual points.

While it is possible to licence individual transmitters using any of the approaches discussed so far it tends to be excessively complex and expensive. Where a single transmitter has been authorised no “change of use” that impacts on deployment is possible (because only a single base station is allowed) and the transmitter power tends to be capped. Other users can then be carefully planned around this transmitter using modelling tools to understand where the same channel can be reused. This planning is mostly performed by regulators although it could be undertaken by a third party “band manager”.