OFCOM

An Assessment of the Effects of Repeaters on Mobile Networks

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EXECUTIVE SUMMARY

Mobile Repeaters are wireless devices which are used in practice to enhance coverage by amplifying and re-transmitting mobile signals to improve coverage in areas where it is poor. On a local level mobile coverage can be enhanced by use of a repeater, but doing so in an ad-hoc way often causes interference to other users, particularly if the repeaters operate outside the direct control of the mobile operator.

Evidence from Ofcom's enforcement team suggests that many of these repeaters have been sold and put into operation. These repeaters are currently sold for typically a few hundred pounds in the retail market. This suggests that they provide a useful coverage enhancement that is not currently provided by the mobile network operators.

In this technical study PA has investigated the likely effect of different repeater implementations on other mobile users. Its main conclusion is that it is possible to make and install mobile repeaters that would not cause any noticeable interference to other users. However the technical features of repeaters sold in the retail market are not sufficient today in most cases to achieve this.

PA has carried out a programme of work to research the availability of repeaters supplied directly to consumers in the UK, and to evaluate their effect on mobile networks. This covered all three cellular standards operating in the UK: GSM, UMTS and LTE. The evaluation of the effects was done by analysis of repeater specifications, laboratory tests on a typical consumer repeater, and simulations of large networks.

The study found that many of the cheaper repeaters on sale in the UK can cause interference to the mobile networks. There is a theoretical basis for this which is also backed up by laboratory tests, simulations conducted as part of the study and the experience of Ofcom’s enforcement team. The problem is that the wideband noise transmitted by the high gain amplifiers used in a repeater can desensitise a base station where the repeater and the base station are within a few hundred metres of each other. Given the number of cellular base stations in the UK, there is a large area of the country that is within this range. The effect is a degradation of coverage for other users, reducing the attractiveness of mobile operators’ services for other users.

The study also considered more sophisticated repeaters available that include various design features to minimise the risk of interference. With these features it is possible to reduce interference to negligible levels. Such repeaters are used today in mobile network operator-approved installations, but could also potentially be made available more widely in the retail market.

The study identified the following set of technical features that can effectively mitigate interference from a repeater:

- Ensuring the repeater only transmits on the relevant uplink channel(s) and attenuates noise on all other channels
- Switching off the uplink transmission when not in use to reduce the combined noise level where multiple repeaters are in use in the same cell
- Reducing the uplink power and noise by means of gain control, or switching off altogether, when close to the base station.
- Ensuring the repeater cannot oscillate if the path loss between its antennas is low

The study noted that the FCC has recently introduced regulations in the USA that permit consumers to self-install repeaters, subject to those repeaters adhering to most of the above features, and the consumer following these procedural steps:

- Obtaining the consent of, and registering the repeater with, their mobile operator before putting it into operation
- Only using the antennas and cables approved for use with that repeater
- Not tampering with the anti-interference features

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1 REPEATERS IN MOBILE NETWORKS

1.1 Why Repeaters are Used

The use of mobile devices has been routine in personal and business life in the UK for many years now. The proliferation of device types and the roll out of ever faster mobile technologies has made their use widespread, not only for voice and text but for many other applications.

Whilst mobile coverage has always been incomplete, expectations have risen and dissatisfaction with 'not-spots' has grown. As mobile devices are used more and more so the impact of gaps in coverage are felt more acutely by the user.

There are sound technical reasons why the coverage provided by the main network will not penetrate certain areas. The walls of buildings, metallisation of windows for thermal reasons, and the use of underground spaces all attenuate the signals between mobile and base station. This attenuation of the signal will lead to a reduction of data rate in 3G and 4G systems, and eventually to a loss of connection in all systems.

Possible solutions include pico-cell base stations and repeaters. A pico-cell is a small, low power version of a conventional mobile phone base station to give fill-in coverage in a limited area. A repeater picks up a signal from the base station, amplifies and re-transmits it in the area of poor coverage; similarly it amplifies and re-transmits the signal from a mobile in the affected area to the base station. This is illustrated in Figure 1.

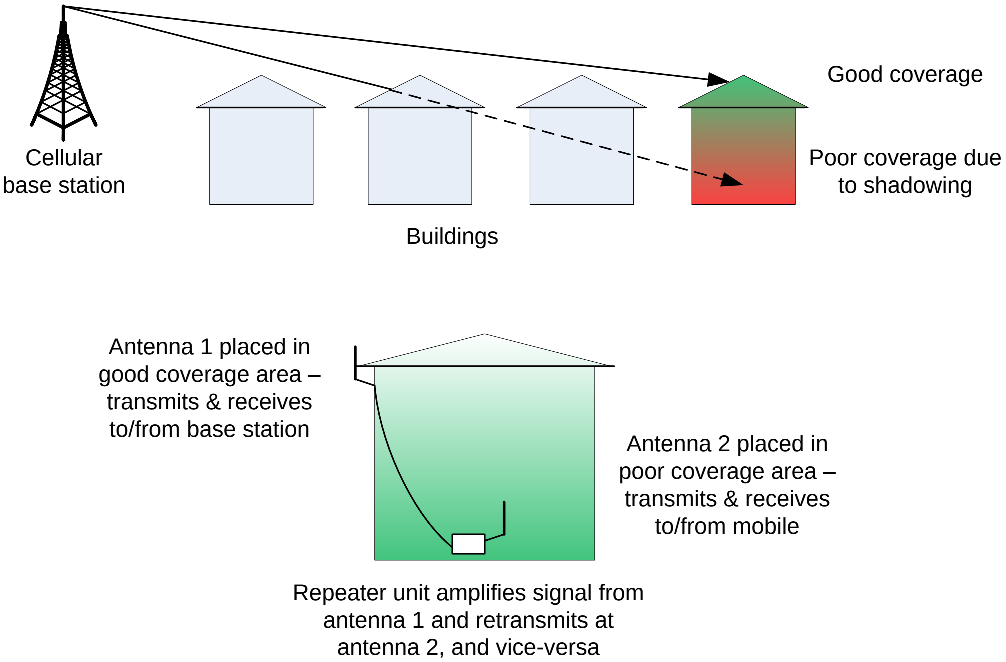

Figure 1. Mobile network repeater

The illustration shows an urban or suburban setting where good reception in the lower part of one building is prevented by shadowing from other buildings in the area. Poor coverage can also occur in other situations, for example:

- In remote areas far from the nearest base station

- In buildings where penetration losses are high e.g. old stone buildings or newer buildings with metallised glass to meet the latest building requirements for insulation.
- In hilly areas where the path from base station to user is obstructed by the terrain
- Inside a metallic vehicle such as a car or train, particularly where the windows are metallised to reduce solar heating

In each case a repeater can still be the solution and will work in the same way as above. The antenna details will vary to suit the particular situation. In remote or hilly locations the reception outdoors may be poor and so Antenna 1 may be a high gain antenna such as a Yagi. The vehicular situation adds the factor that the repeater itself is mobile, which has implications that are discussed in section 2.

1.2 The Economics and Legalities

The cost to the network operator of the manpower and equipment needed to plan and install a pico-cell or repeater is likely to be tens of thousands of pounds for each instance. This means that the cost cannot be justified by the increased revenue where only a small number of subscribers will use the enhanced coverage. This is typically the case for consumers and small businesses in localised not-spots.

Users in this position are currently left with limited options. Some operators offer femtocells that connect to a fixed broadband service and provide a cell with coverage of typically up to 50m radius. They require a broadband connection which may not be available in every case. They are restricted to a single operator and so may not be convenient where multiple users are involved.

Operator-approved repeaters suitable for home use are available from some companies. These have features to prevent interference to the networks. One implication of this is that they, like femtocells, are restricted to a single operator. Multi-operator units are available that consist of independently-functioning repeaters for each operator. Such units inevitably cost more than single-operator units.

A third route is also possible; that of the unapproved repeater. These devices are typically very simple, repeat the whole band (or multiple bands) and can cause interference to the networks due to their ad-hoc installation. As a result they may infringe the Wireless Telegraphy Act. Nonetheless they are on sale openly in the UK. Ofcom's enforcement team has seized nearly 400 repeaters in the last few years following reports of interference.

2 THE INTERFERENCE PROBLEM

The mobile networks are carefully planned to maximise coverage and capacity with a finite amount of radio spectrum. This involves plotting the signal strength from each antenna of each base station in detail and co-ordinating frequencies (or scrambling codes for 3G) between base stations.

The network operators install repeaters themselves, or via approved contractors, to enhance coverage in some areas. They avoid interference problems by planning the signal levels and frequencies to fit in with their wider network. The repeaters will also usually operate on one network only.

The types of self-installed repeaters operated in the UK typically take the whole of a mobile band, amplify and re-transmit it. Signal strengths and noise levels across the whole band will be increased, meaning that all networks operating in that band are affected. In addition the signal levels are not planned in the way that they are with operator-installed repeaters. Fixing a coverage problem for a small number of users can result in degrading coverage for a much larger number of users.

There are several different mechanisms by which a repeater could interfere with the operation and performance of the mobile network.

- Raising the noise floor on the uplink signal
- Raising the noise floor on the downlink signal
- Blocking (overloading) the base station receiver
- Disrupting the uplink power control
- Oscillations and spurious emissions
- Distortion or delay of the signals

Some of these are not significant in practice for various reasons, all are described in more detail below. A quantitative analysis to determine the dominant mechanism is described in section 3.

2.1 Raising the Noise Floor - Uplink

The repeater will transmit not only the wanted signal but wideband noise. This is because, like any electronic device, there is thermal noise inherent in its components. Appendix A explains how noise levels are calculated. The combination of the amplifier gain and noise figure means that the noise floor at the output could plausibly be 80dB above thermal noise. In addition any noise at the input from external sources will be amplified along with the wanted signal.

If there is a relatively small path loss from the repeater to the base station then the noise transmitted by the repeater can be above the sensitivity level of the base station's receiver. In this case the base station's effective sensitivity is reduced.

For mobiles at the edge of the cell, already operating at the upper end of their power control range, the uplink connection will be lost. The user will see the symptom as a dropped or blocked call even if their mobile shows there is network coverage. The mobile is at the cell edge so the interference mostly affects mobiles that are some distance away from the repeater. The operator will see a worse than expected signal to noise ratio (SNR) in their network monitoring system.

In 3G and 4G systems the data rates are variable for each link and in total. Increasing the noise floor reduces the SNR. This causes an increase in bit errors that in turn will cause the radio link control to increase the mobile's power. If it is not possible to increase the mobile's power, either because it is at maximum already or for load balancing reasons, then the data rate will be reduced. The effect of the repeater noise is therefore to reduce the capacity of the cell even if the connection is not dropped. This will affect all users in the cell.

2.1.1 Other Network Interference

This situation is most likely to occur when the user is in a poor coverage area for their network operator, but a good coverage area for another operator (see Figure 2). It is the second operator's base station that is interfered with. Thus the affected mobiles are not only distant from the repeater but on a different network to the repeater user.

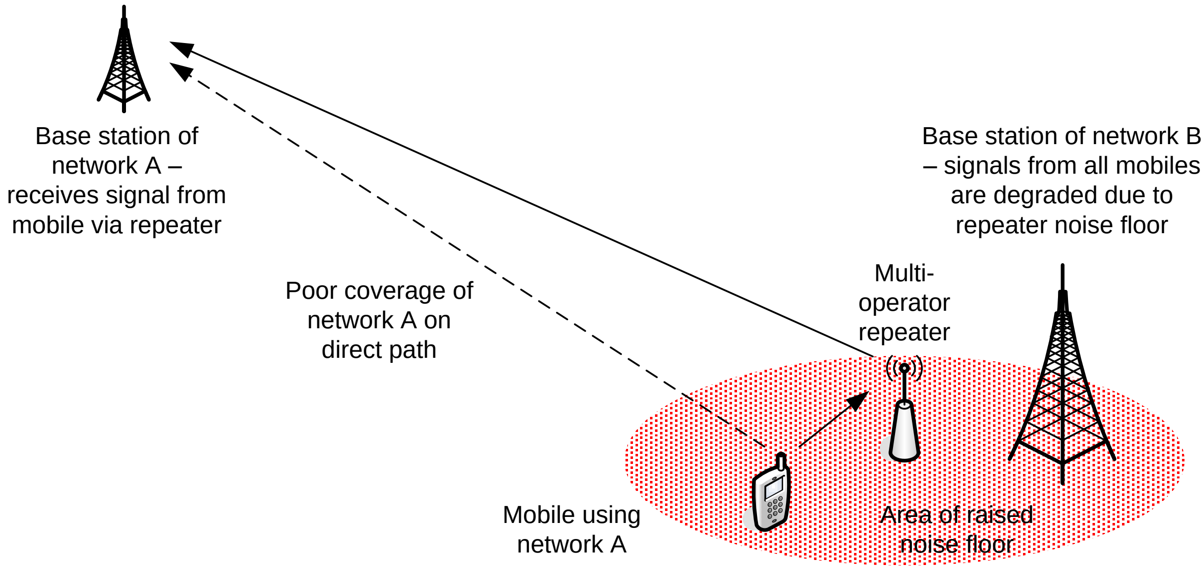

Figure 2. The near-far problem in the uplink

Repeaters that only operate on a single network avoid this interference mechanism. In addition any repeaters installed by the MNO can be planned to have locations, power levels, antenna patterns etc that avoid the problem.

2.1.2 Same Network Interference

This situation occurs where the outdoor coverage is good but there is a high penetration loss to the user's location. This may be at the centre of a large building such as an office block or hotel with many rooms; it may be the basement floors of a shopping centre or multi-storey car park; or it may be inside a vehicle or building that is largely metallised for reasons of thermal insulation.

In these cases the wanted base station may be quite close to the repeater, and so is affected by the raised noise floor. This reduces the coverage area for other mobiles that are on the same cell but outside the repeater's coverage.

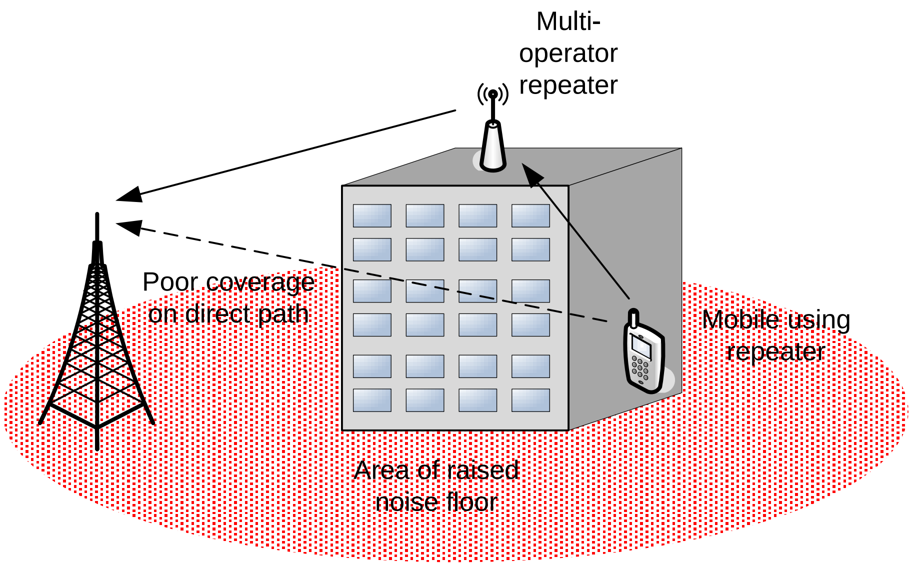

Figure 3. The low path loss problem

Since the path loss between repeater and base station is relatively low, the gain can be reduced and with it the noise floor. This requires some degree of automatic gain control in the repeater's uplink, based on the signal level received in the downlink. For a multi-operator repeater to be effective both in preventing interference and as a repeater, the gain control will need to act separately for each operator's spectrum.

Cascaded repeaters are a particular problem. If repeater A is used to provide coverage to repeater B, then on the uplink the noise out of repeater B is further amplified and added to by repeater A. This can create a much higher noise level than one repeater alone.

2.2 Raising the Noise Floor - Downlink

The mechanism for raising the noise floor in the downlink is similar in nature to that in the uplink, except that it is the mobile's receiver that is affected. As the repeater's downlink output power is a lot less than a macro base station, it is only mobiles near to the repeater that will be affected.

The wanted output signal is amplified from a weak level to a much stronger level, that being the purpose of the repeater. For a multi-operator repeater the noise level is raised for all mobiles in the vicinity, but so is the wanted signal. A mobile that is currently receiving a good signal may suffer a reduction in SNR. However there is unlikely to be a significant interference problem from this effect. Mobiles that are currently receiving a weak signal are likely to benefit more from the increase in wanted signal than they suffer from the increase in noise – this is the purpose of the repeater.

2.3 Base Station Receiver Blocking

The repeater will transmit the signal from the mobile after amplifying it. If the repeater is near to a base station and at full gain then the signal at the input of the base station's receiver will be at a high level. If the level is too high then the receiver will be overloaded and it the reception of other mobiles will be degraded or stopped entirely. This process is known as blocking.

In practice GSM, UMTS and LTE systems all use uplink transmitter power control (ULPC). This is particularly important in UMTS due to the use of code division multiple access (CDMA). The base station measures the signal level that it is receiving from a mobile and continuously instructs the mobile to increase or decrease its transmitter power. This maintains the signal level at the base station at its optimum level. An increase in the path loss to the mobile will result in the mobile being instructed to raise its power, until it is at maximum power. Any further increase in path loss will cause the mobile to go out of coverage.

If the repeater gain is fixed then the ULPC function still works correctly. In this case the ULPC will adjust the mobile's transmit power as required and the repeater will not cause blocking.

2.4 Power Control

If changes in the mobile's transmit power are not carried through the repeater then the ULPC breaks down, causing blocking as described above. There are two apparent routes by which this may happen:

- The repeater is at its maximum power level. This has the same effect as the mobile reaching its maximum power – the mobile goes out of coverage
- The repeater employs gain control that maintains a steady output power on the uplink. This will defeat the ULPC and is likely to reduce the capacity and/or coverage of the cell

3G systems are particularly sensitive to a failure of ULPC. If a mobile's power is too low it will be dropped; if it is too high it will reduce the capacity of the cell for other mobiles.

The potential for interference to the cell therefore depends on the gain control, if any, that is used. Maintaining a constant gain is not a problem, maintaining a constant output power is likely to cause interference.

2.5 Oscillation and Spurious Emissions

At its simplest a repeater consists of two amplifiers, one for the uplink and one for the downlink. Diplexers are fitted to allow the output of one amplifier and the input of the other to use the same antenna. The main signal path for the downlink is from the base station to one antenna, through the downlink amplifier, and from the second antenna to the mobile. The reverse path applies to the uplink.

However there exists another path that is unintended – the path between the two antennas. This acts as a feedback path from the output to the input of each amplifier. This is illustrated in Figure 4.

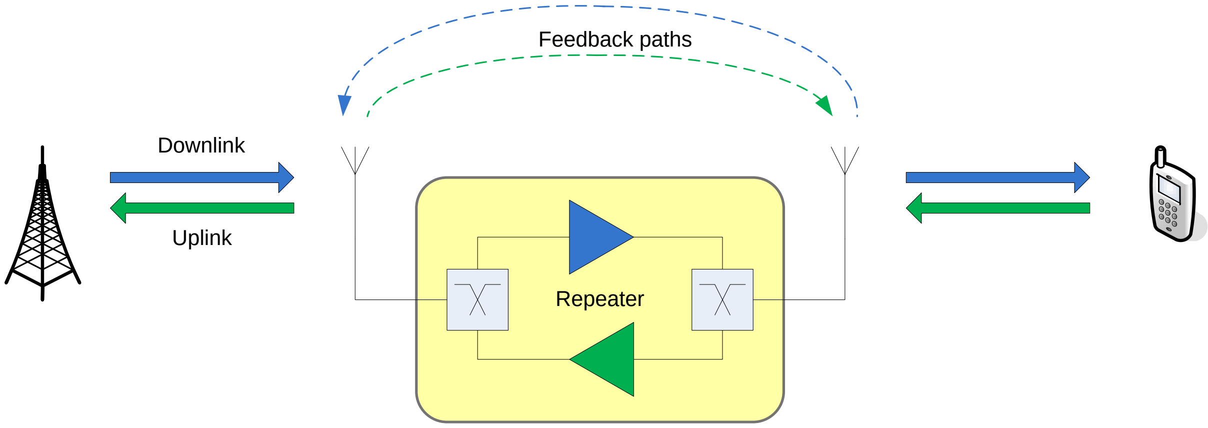

Figure 4. Feedback paths around a repeater

If the loss on the feedback path is less than the gain through the repeater then it will oscillate. The oscillation will occur in the operating frequency band and will be at the repeater's saturated output power. The effect on a base station or mobile using the oscillation frequency is that the repeater will act as a jamming transmitter.

Many of the available repeaters have gains of over 50dB, which is a plausible path loss between antennas that are within a few metres of each other. For this reason, some repeaters include anti-oscillation features. Details are not disclosed but it is believed that these detect the feedback condition and reduce the gain as required to maintain stability.

A similar effect is that of spurious emissions. These are signals that are generated internally within the repeater from various sources. They could be at any frequency but those within the operating band are likely to be amplified and so cause greater levels of interference.

2.6 Distortion and Delay

The repeater will not only amplify the wanted signals, in any real system it will also delay and distort them to some extent. The receivers in the mobile and base station can tolerate a certain amount of distortion without a problem, but excessive distortion will cause bit errors leading to a lowering of quality of service. The effects will be the same as for high noise levels: dropped or blocked calls, and reduced data rates. This will occur even when the receiver is picking up a strong signal. The distortion in the repeater is usually greatest when the signal level is high.

Another symptom of distortion is power being spread into the channels immediately above and below the main signal – the adjacent channels. This will raise the noise level in the adjacent channels and so increase the likelihood of interference to any base stations or mobiles operating on those channels.

The delay through the repeater is mostly due to the filtering and signal processing rather than the amplifiers themselves. There is an inherent delay in both downlink and uplink paths anyway due to the speed of propagation and the distance between the mobile and base station. A distance of 300m gives a delay of 1µs. A cellular mobile system is designed to cater for variable delays in the signal path as the mobile moves around. Different standards have different limits on round trip time (the time for the radio signal to travel from base station to mobile and back again) but they equate to a maximum range that is usually tens of km. Adding delay in a repeater will take up part of this maximum round trip time and so reduce the maximum range.

For most simple repeaters the delay is specified at ≤0.5µs one-way. This means it reduces the cell radius limit by no more than 150m. In practice the cell is nearly always limited by path loss to a lower radius than the timing limit and a reduction of 150m is unlikely to change this. The delay in the repeater is therefore unlikely to have an effect on cell coverage.

Smart repeaters may have longer delays due to the signal processing and more demanding filtering involved. A 5µs one-way delay will reduce the cell's maximum range by 1.5km. Unlike the noise problem, this range reduction affects only those mobiles using the repeater. Those operating directly with the base station are unaffected.

2.7 In-Vehicle Repeaters

Repeaters are available for installation on board a car, bus, train or boat. The lack of cellular coverage on trains has been described in a previous report by PA for Ofcom[1]. There have been a number of repeater installations on trains in the UK, with the train operators and one or more MNOs working together. The key point is that each repeater works on one MNO's network only and is under the control of that MNO. Multiple repeater modules have been installed together to provide coverage for multiple MNOs. This approach addresses both the technical problems that cause interference. The number of mobile users on a train provides the economic justification.

In-train repeaters are invariably professionally designed and installed with the full backing of the relevant MNO(s). However in-car kits are also available for installation by consumers. These are essentially the same as the consumer in-building repeaters but with accessories more suited to a vehicle, e.g. magnetic-mount antennas and 12V rather than mains power supply.

Repeaters mounted in vehicles will themselves be moving. The problem of a repeater operating close to a base station and raising the noise floor (see section 2.1) will occur from time to time as the vehicles pass base stations. For a repeater that operates across the whole band it will affect all networks in the band, including the wanted network. It would be possible to dynamically alter the repeater gain as the signal from the base station varies, but the implementation will need to be done in a way that avoids the power control problem (see section 2.4).

[1] Not-spots research: Impacts, causes and potential solutions for areas of poor coverage, April 2010

3 ANALYSIS

3.1 The Key Questions

Several questions need to be answered to find out what makes a repeater interfere, or not, with a mobile network:

- What repeater types are available or may become available?
- Which interference mechanisms have a significant impact on the network?
- How much do specific characteristics of the repeater affect this impact?

3.2 Our Approach

To answer these questions we have used a combination of three approaches: researching and categorising the available repeaters; laboratory testing of a representative repeater; and simulations to extend the test results to a wider set of scenarios

3.2.1 Categorisation of Repeaters

There are many different types of repeater available for UK consumers to order online from several websites. We first produced a ‘long list’ of models available with their advertised characteristics. These included the basic description (operating bands, typical coverage area, fixed or vehicular use) and more detailed specifications where available (e.g. gain, noise figure, channel selection and gain control details).

There were models available from different sources that appeared very similar if not identical. In addition various models from each retailer had differences only in operating bands or coverage areas. The second stage of the analysis was therefore to group the repeaters into categories – the ‘short list’.

In particular, the repeaters’ specifications were grouped according to any ‘smart’ features such as automatic gain control or selectivity between operators.

Finally we looked at what was available and compared it with developments in mobile technology. We also spoke with some of the existing manufacturers of smart repeaters. From these sources we have forecast some developments in repeater products over the next few years.

3.2.2 Lab Tests

A repeater was selected from those identified above for testing in PA’s laboratory. It was chosen to be typical of those marketed for use in home and small offices and to support GSM, 3G and LTE. A dual-band 900/1800MHz device was chosen as this band combination covers all three standards in the UK. The particular model used also had on/off and manual gain control for each band.

The testing was carried out using cabled connections for all except the mobile phones used in the second phase; these were placed inside RF screened boxes with an internal antenna. This was done so as to avoid the interference problems that are the subject of this study.

RF Characterisation

The first phase of testing was to measure the RF characteristics:

- Gain, including frequency response
- Maximum output power
- Noise level

- Harmonics and spurious emissions
- Distortion
- Delay
- Stability (oscillation)

To do this a signal generator and spectrum analyser were used with attenuators to set the signal levels as required, as shown in Figure 5. This was performed four times to cover the permutations of uplink and downlink, 900MHz and 1800MHz bands.

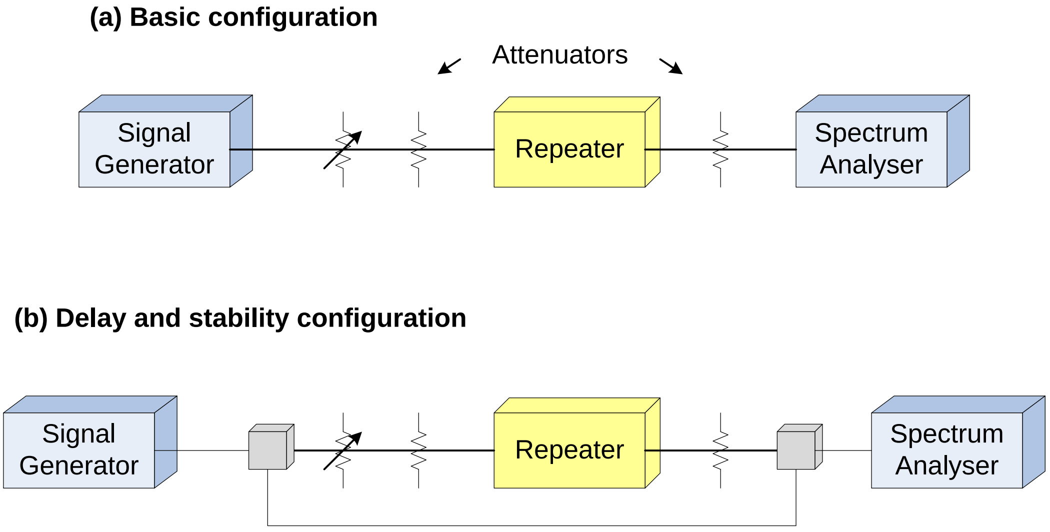

Figure 5. Measurement of RF characteristics

Network Emulation

The second stage of testing was to emulate mobile networks in operation, and to see the effect of adding a repeater. To do this it is necessary to set up a ‘victim link’ that receives noise from the repeater. This is done with a network emulator and corresponding mobile phone – the phone is inside a screened box to avoid the test interfering with any live networks. The repeater is driven by a signal generator as previously, and its output is added to the uplink signal in the victim network as shown in Figure 6.

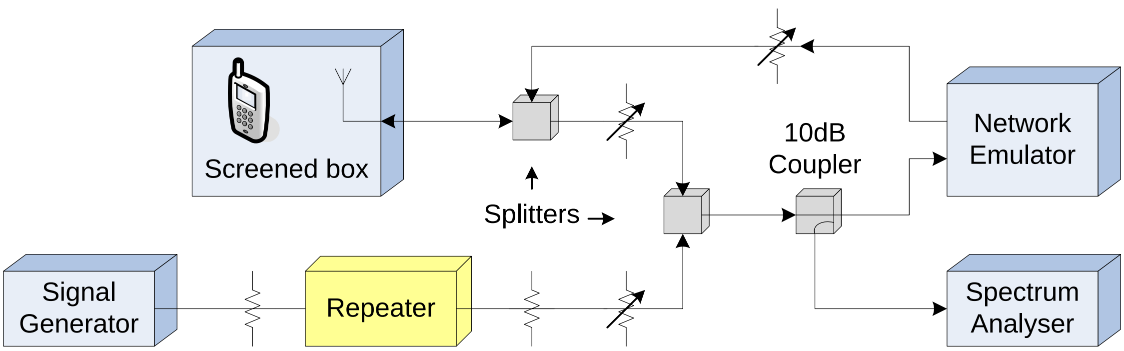

Figure 6. Measurement of effect on networks

The variable attenuators enable independent control of the path losses on the uplink and downlink, and from the repeater to the base station. The mobile used was a Samsung Galaxy S3, which is a multi-standard smartphone covering GSM, UMTS and LTE. By varying the emulator configuration the victim link can be set to the three standards in turn.

The maximum path loss that can be reached between the network and mobile was measured with the repeater switched off. This was done by putting the mobile into a call for GSM and UMTS, or measuring the block error rate (BLER) for high-rate data on LTE, then increasing the uplink path loss. The repeater was then switched on, and the maximum mobile path loss re-measured for various levels of repeater path loss.

The Effect on a Mobile Network

The network emulator's sensitivity is worse than that of a real base station. As a result the absolute path loss values measured cannot be mapped directly onto a real cell. Instead the differences between the mobile's path loss and the repeater's path loss were used.

The repeater's noise floor is less than the mobile's transmitted power by more than the required SNR. The mobile's path loss can therefore be greater than that of the repeater. The amount of excess path loss that can be tolerated before the cell's performance degrades was calculated from the measurements.

The maximum path loss for the mobile in the absence of a repeater is known from the relevant 3GPP standards plus typical specifications for mobiles and base stations. These were set at 160dB for the GSM and 3G networks and 142dB for the high data rate LTE network. Combining this with the previous step gives the path loss for the repeater below which interference is likely to occur.

Finally, the ranges corresponding to the maximum mobile and minimum repeater path losses can be predicted. The 3GPP standard COST-Hata propagation models were used for this, with the results calculated for a quasi-rural environment.

The results show how much of a cell area is at risk of degraded performance due to noise from a repeater of the type measured.

3.2.3 Simulations

The lab tests are useful to confirm the interference effects and to measure them. However it is only practical to emulate a single base station for each network using this approach. To extend the analysis to cover the wider network it is more appropriate to use simulations.

The simulation tool used was SEAMCAT[2], developed by the European Communications Office (ECO) specifically for analysing radio interference problems. It includes built-in configurations for CDMA and OFDMA networks. SEAMCAT uses the terms 'interfering' and 'victim' to refer to the networks or mobiles that are the source and recipient of the potentially interfering signal.

Three victim networks were set up representing GSM, UMTS (3G) and LTE. Uplink and Downlink were simulated in turn. These used mobiles randomly distributed over the coverage area as would be expected for a real network. A wide-area network of base stations was used with the exception of GSM for which a single base station was modelled. This is because the interaction between adjacent base stations is much more limited in GSM compared to 3G and LTE.

The parameters of the victim network and mobiles were set to the figures in the 3GPP standards with one exception. The LTE receiver blocking level was set at -65dBc as this was felt to be more representative of a real base station receiver than the minimum figure of -43.5dBc quoted in the 3GPP standard. Typical figures were used where there were options within the standards.

The interfering network was set up as a single transmitter representing the repeater. This was operating at a frequency 5MHz above the centre frequency of the victim network. The transmitter was given the parameters that were measured on the 900MHz uplink of the example consumer repeater:

- +18dBm transmitter power
- A noise floor of -61dBm per 100kHz bandwidth

Key parameters used in the simulations are given in Appendix C.1.

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[2] http://www.cept.org/eco/eco-tools-and-services/seamcat-spectrum-engineering-advanced-monte-carlo-analysis-tool

SEAMCAT provides random distribution of the mobiles' location as described above, and statistical variations to the propagation conditions for both mobiles and repeater. In addition to these built-in variations, two inputs were varied to establish the sensitivity of the interference to these parameters:

- The distance from the repeater to the base station
- The noise floor of the repeater

The output parameter was chosen according to the network technology being modelled, as described in section 4.3. 120 instances of each simulation scenario ('events' in SEAMCAT terms) were run and the average result was taken. This number of instances was found by iteration to be sufficient to give a reasonably small degree of variation in the results from repeat runs of the same scenario.

4 THE RESULTS

4.1 Categorisation of Repeaters

The categorisation of repeaters was conducted after a detailed research of repeater products available on the market. It was decided to avoid contact with retailers or manufacturers therefore the research was based on the information available on the respective web sites.

4.1.1 Repeater suppliers

Three groups of repeater suppliers have been researched:

- Specialised repeater retailers
- General electronics retailers
- Repeater manufacturers.

4.1.2 Categorisation criteria

The repeaters have been classified by four main criteria:

- *Smartness* – advanced features such as automatic gain control, selective repeating for particular operator or frequency sub-bands, other types of connectivity such as Bluetooth
- *Coverage area* – related to the maximum output power
- *Spectrum bands* – whether they support single, dual, or multiple frequency bands
- *Price* – an indicator of accessibility of the devices to the mass market.

Several other criteria were considered but were not used in the grouping because they did not provide for sufficient differentiation. These were:

- *Noise figure* – most repeaters for which this parameter was available quoted a noise figure under 6dB, with a few others up to 8dB.
- *Maximum gain* – the gain, or maximum gain if controllable, provided by a repeater. This parameter is related to the output power and hence the coverage area.
- *Time delay* – all simple repeaters where this figure is available quote a delay of less than 0.5µs. Delays between 6µs and 9µs were quoted for repeaters with channel filtering. This split is therefore covered by the Smartness category.
- *Voice or data* – some repeater suppliers state explicitly for some repeater types that they are only for voice and/or data. This appears to be aimed at the less technically savvy mass market, because the “voice only” refers to GSM bands, voice+data refers to 3G bands, and data only refers to 4G bands. Therefore such differentiation is in fact related to frequency bands, which is covered above.
- *Number of users* – some suppliers list explicitly the supported number of users. This is related to the maximum output power of the repeater – the higher the power, the higher the number of supported users. Again, this is under the Coverage Area category.

Smartness

Simple - most of the cheaper repeaters are simple and repeat an entire cellular band. They are not selective upon a particular operator or frequency sub-band and have fixed gain in uplink and downlink.

Manual gain control - some of the repeaters allow manual gain control, mostly the dual band versions but also some single band ones.

Automatic gain control (AGC) - some smart repeaters in the UK have both manual and automatic gain control.

Automatic gain control Plus (AGC+) - most repeaters from certain companies have intelligent AGC with feedback detection, oscillation control, and base station proximity awareness. They detect whether a mobile is currently using the repeater and switch off the uplink transmission if not.

Individual sub-band control - repeaters from some manufacturers select the sub-bands used by individual operators. For some, the repeater is configured before sale to use only one specific operator's spectrum; others allow the setting of individual gains and automatic level control settings for each operator's sub-band.

Auto-configuration and additional connectivity - various means of remote control and configuration are available. Some repeaters are operator-specific and partially decode the cell's broadcast signal to verify that they are repeating the correct operator. This design also allows an operator to shut down repeaters using its cells, either across a whole cell or individually by serial number. Some of the latest repeaters have Bluetooth Low Energy communication for configuration via a mobile handset. Other repeaters have configuration control via a web interface. The newest digital repeaters also have auto-configuration functions.

Coverage Area

The quoted coverage area is closely linked to the maximum output power of the repeaters. The commercially available repeaters can be split into five different coverage categories as shown in Table 1.

Table 1. Coverage area

Quoted coverage area	Typical max output power
150 - 250 sq m	~ 17 dBm
~ 500 sq m	~ 20 dBm
1,000 – 1,500 sq m	~ 21 dBm
2,500 – 3,000 sq m	~ 23 dBm
~ 5,000 sq m	~ 27 dBm

All repeater suppliers have devices with coverage across the whole range, with one exception that has a single range device of up to 1,207 sq m (13,000 sq ft). One manufacturer has devices with different ranges for professional installers, however for end users they are marketing devices with an output power of 20 dBm which typically corresponds to 500 sq m coverage area.

The maximum gain for simple repeaters depends on the coverage area, the smaller the area, the smaller the gain. For example, one range quoted as 250 to 500 sq m coverage has maximum gain 55 to 60 dB, the devices for 1,000 to 2,500 sq m have gain in the range 60 to 65dB, and devices with larger range can go up to 75 dB. A summary is shown in Table 2. Smart repeaters with advanced gain control algorithms can achieve higher gains of up to 100 dB.

Table 2. Maximum gain

Max coverage area	Typical maximum gain
150 to 500 sq m simple	55 to 60 dB

1,000 to 2,500 sq m simple	60 to 65 dB
Over 2,500 sq m simple	65 to 75 dB

Spectrum Bands

There is a wide range of devices which cover from a single band up to the full range of five bands. The older and simpler devices tend to support the established GSM/3G bands at 900, 1800, and 2100 MHz. The newer and smarter devices tend to support also the bands at 800 and 2600 MHz, which are likely to be used for LTE. The used bands are summarised in Table 3.

Table 3. Spectrum bands

Number of bands	Covered frequencies
Single band	800 MHz 900 MHz 1800 MHz 2100 MHz 2600 MHz
Dual band	900 and 1800 MHz 900 and 2100 MHz 800 and 2600 MHz
Tri-band	900, 1800 and 2100 MHz
Quad-band	800, 900, 2100, and 2600 MHz Four bands out of 800, 900, 1800, 2100, 2600 MHz
Penta-band	800, 900, 1800, 2100, and 2600 MHz

Some repeaters consist of two units with a wireless link between them. These are so that one unit can be placed in an area of good coverage and the other in the area for which coverage improvement is required, without needing a long cable between them. They are used with large separations (e.g. hilltop and valley) to provide remote area coverage, and small separations (e.g. attic and living room) to provide indoor coverage.

Although the wireless link often uses a different frequency band to the main cellular bands, they are not counted as an extra band in this context. This is because the link is internal to the repeater and does not provide any extra band coverage to the end user.

Price

The price is related to the “smartness” of the repeater, the range, and the number of supported spectrum bands. The simplest single-band no control repeaters are consistently cheapest at around £135. Adding manual or automatic gain control does not affect the price greatly, whereas adding bands and increasing the power can increase the price to £1500. Smart repeaters are more expensive at £500 to £2000 depending on specification whilst the most expensive is a tri-band high power repeater at £6495.

The price ranges are illustrated in Figure 11.

4.1.3 Grouping

The long list of repeaters available in the UK was analysed for features according to the above categories. The numbers of repeaters in each category are shown in Figure 7 to Figure 10.

It should be noted that the number of repeaters on sale is not the same as the number sold and in use. Sales figures were not available, but it is likely that the cheaper models in general sell faster than the more expensive ones. The graphs below are arranged with the lower cost features on the left and higher cost on the right. Therefore the slope across the graphs is likely to be enhanced when considering the number of repeaters deployed.

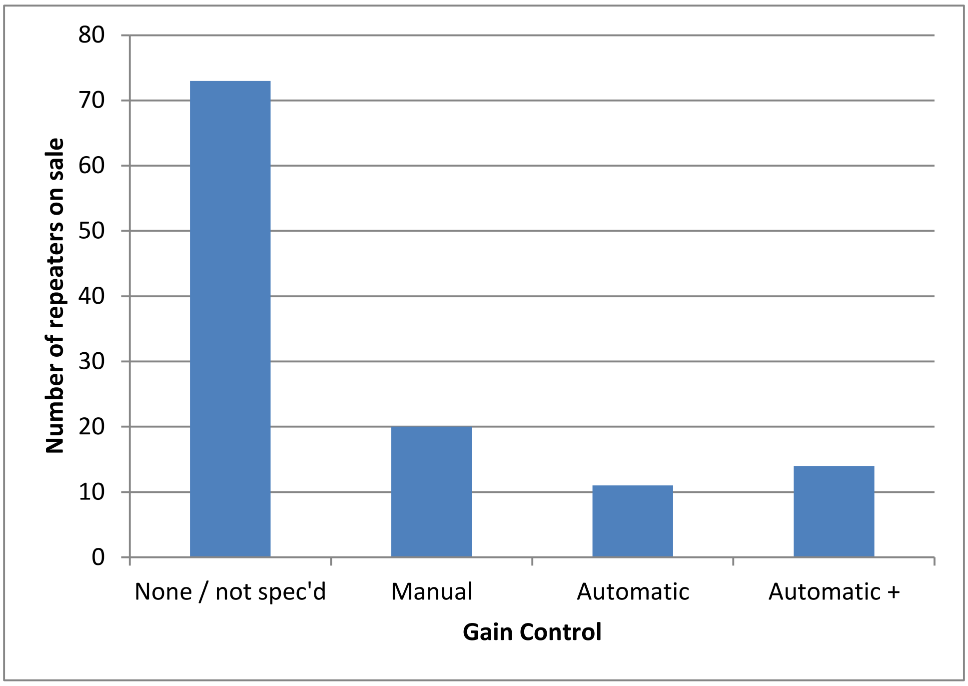

Figure 7. Repeaters categorised by gain control

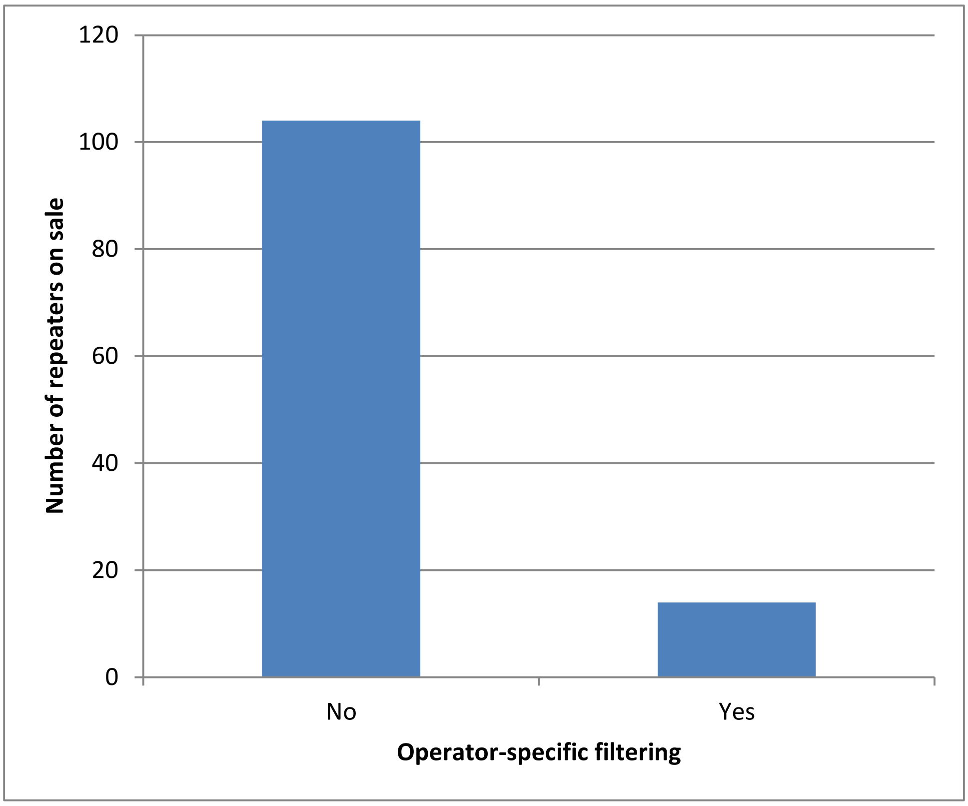

Figure 8. Repeaters categorised by channel filtering

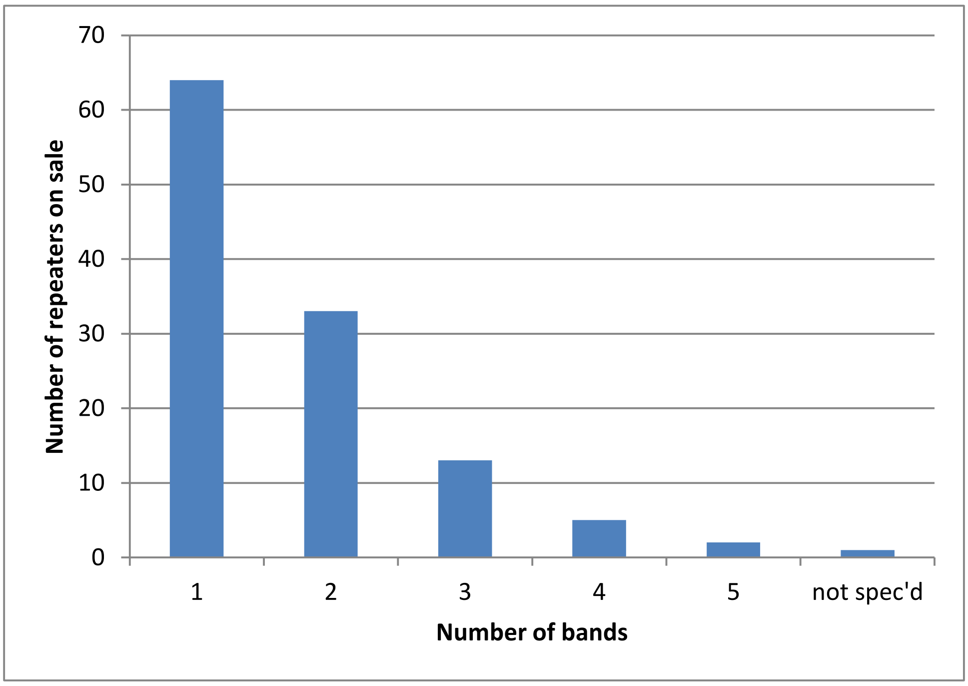

Figure 9. Repeaters categorised by band coverage

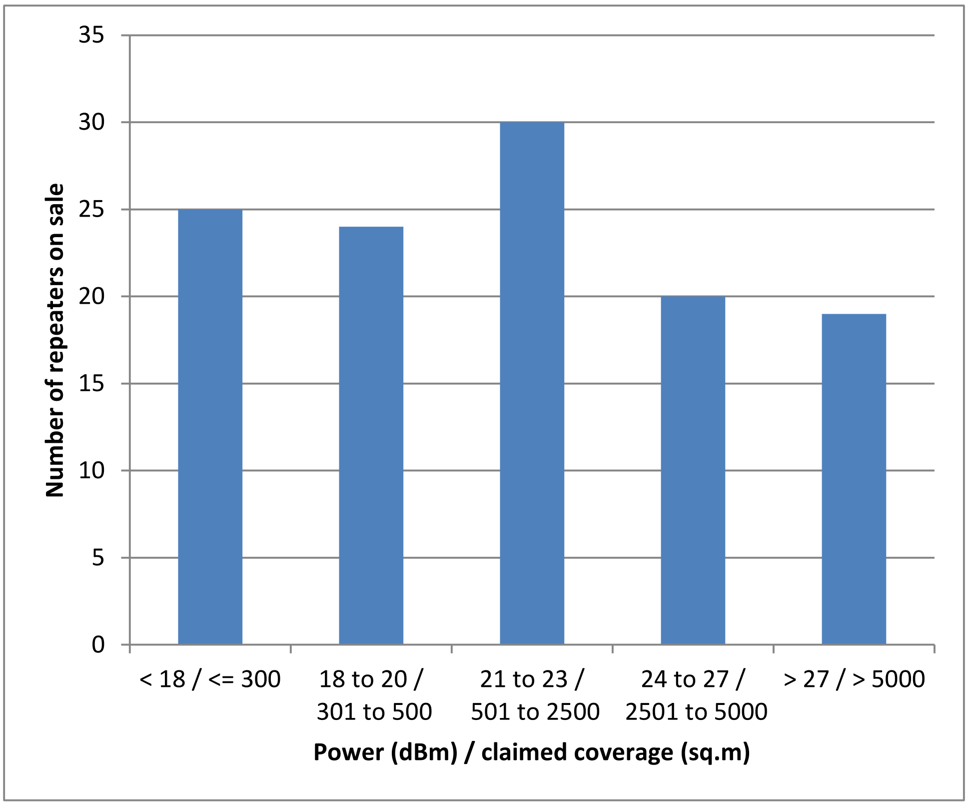

Figure 10. Repeaters categorised by power and coverage area

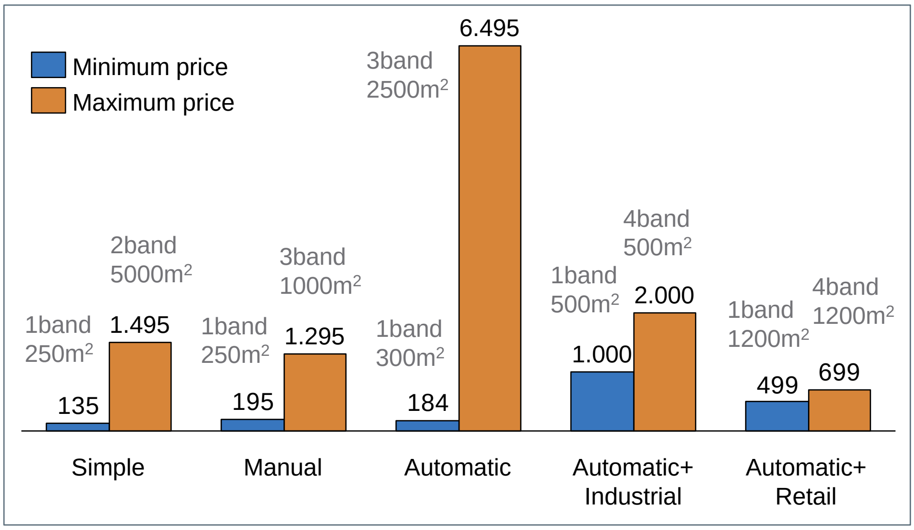

Figure 11. Repeater pricing categorised by complexity

4.1.4 Evolution

The preceding sections look at what is on the market to UK consumers and small businesses today. From discussions with industry and consideration of wider trends, PA has identified several areas in which repeaters may evolve over the coming 5 to 10 years. Some of these may require regulatory changes to enable them in the UK:

Market

Repeaters will increasingly be used in cars and trains, and possibly buses, due to the increased use of metallised glass for thermal reasons. Some of the more upmarket car manufacturers are understood to be looking at fitting repeaters as original equipment. BMW announced recently that it is developing a femtocell for in-car use[3] - whilst this is different to a repeater it shows the demand for improved in-vehicle coverage is taken seriously by the car manufacturers.

Conversely, car manufacturers are starting to install built-in mobile phones for emergency calls. In the longer term it may be possible to use these as remote cellular modems for the user's own phone. In that case the requirement for an in-vehicle repeater would go away.

Buildings that are new or subject to major refurbishment will increasingly have repeaters or other mobile coverage solutions installed as part of the build. Buildings with large numbers of people e.g. airports and sports stadia often have such installations anyway. This is likely to spread to smaller, private buildings as the costs involved come down and expectations of mobile coverage increase.

Consumer telecom contracts are often sold as 'bundles' in the UK today – a combination of two or more of fixed phone, mobile, cable TV, and broadband. In order to make the mobile offering more attractive a femtocell or repeater may be included in a consumer unit, in the same way that a WiFi router or TV decoder is included at present.

There is a growing trend to enable WiFi calling from smartphones, which uses the data connection provided by WiFi to off-load voice traffic from the cellular network. The feature is available on the latest Androids, Lumia, and iPhones and is already provided by a number of operators around the world. In the UK, Three and O2 are already providing WiFi calls through additional apps. EE is trialling a WiFi calling service integrated in the main dialler of the mobiles (no extra app is needed), and Vodafone is expected to launch a service similar to EE in the summer of 2015. There are also plans to expand the service and enable handover between cellular and WiFi which will in effect turn any WiFi into a femtocell at a fraction of the cost.

A related trend is the move towards LTE in unlicensed spectrum (LTE-U). While standardisation efforts focus on using LTE-U to expand capacity, it is technically possible to also use it to expand coverage. LTE-U is favoured by some operators over WiFi because it allows them to retain better control over access and link quality. Verizon and T-Mobile in the USA are already running trials and base stations/handsets supporting LTE-U are already on the market. Current LTE-U implementations cannot work standalone – they need an LTE service in a licensed band which can then hand over part of the traffic to LTE-U in unlicensed 5GHz and 3.5GHz spectrum. However it is plausible that in future standalone LTE-U cells could be used for expanding coverage without affecting the licensed bands.

These last two points illustrate that the longer term demand for repeaters may reach a natural limit as alternative means of connection grow in popularity. Holes in cellular coverage will become less critical and the alternatives will be cheaper solutions for consumers to adopt.

Technical

There is a long term trend in consumer electronics products towards lower cost and improved features over time. Repeaters will inevitably follow this trend. As a result some features that are only in the more expensive repeaters currently will become cheaper or included as standard in basic models. This is likely to apply particularly to features such as intelligent gain control and anti-oscillation algorithms that are relatively low cost additions to a simple repeater.

Two of the manufacturers of smart repeaters include facilities for remote control of their devices. Direct control by operators via cell broadcast signals is used by one, whilst the other uses a web interface. Such control is relatively low cost to implement in a smart repeater since much of the hardware is

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[3] BMW press release 2nd March 2015

already in the design for other reasons. As the intelligence of repeaters increases, so the ability to remotely control them is likely to increase too.

The remote control of repeaters requires some form of connection. This could be via the cell broadcast or an Ethernet connection as above. Some higher-end consumer repeaters are appearing with Bluetooth or WiFi connections, enabling control from a mobile. This will make it much easier for the consumer to set up the repeater as presumably they will have a mobile anyway.

Some repeaters designed for larger installations, e.g. multi-storey offices and hotels, include the switching between antennas to direct coverage to where it is required. This includes aspects of distributed antenna systems (DAS) that are used with conventional cells for indoor coverage.

The combination of various developments above means that the distinction between different types of coverage solution will become blurred. Using a mobile to control a smart repeater, small cells with mobile backhaul (e.g. the BMW in-car solution) and "MiFi dongle" type devices will have overlapping feature sets.

Procedural

Two procedural aspects that are currently in use in the USA could be foreseen working in the UK also. Firstly, consumers are required to register self-installed repeaters with operators. It is possible that such repeaters could include features that require registration before they will operate. Secondly, the FCC publishes a specification[4] that includes anti-interference features, which repeaters must comply with to be eligible for consumer installation. Any repeaters not complying with the specification, e.g. because they have a higher transmit power, must be professionally installed.

MNOs currently approve installation of repeaters by suitable contractors on a case-by-case basis. This approval process takes time and the cost would be prohibitive for consumers. A move towards a list of approved contractors who could carry out repeater installations without reference to an MNO would be a logical progression. There is an analogy with other installers who require certification for safety reasons e.g. gas fitters and electricians.

4.2 Laboratory Tests

4.2.1 RF Characterisation

Gain, Frequency Response, Noise

The repeater under test had variable gain on each band, over a range of nominally 29dB to 60dB. The gains and frequency responses were measured at minimum and maximum gain; the noise levels were measured at maximum gain as it was below the spectrum analyser noise floor at minimum gain. The full results are tabulated in Appendix B.1.1.

The frequency responses are shown graphically below. The 900MHz band appears to be using P-GSM rather than E-GSM filters. This means the bottom of the band is attenuated by up to 34dB on the uplink and 71dB on the downlink compared to the upper part of the band. At the peak of the frequency response, the uplink gain is 3dB below nominal and the downlink gain varies from 8dB low (29dB nominal) to 2dB high (60dB nominal).

The 1800MHz uplink shows a drop of 7 to 8dB in gain towards the top of the band but otherwise the gain is fairly flat on both uplink and downlink. The gain in the centre of the band was 1dB below nominal on the uplink, 1 to 4dB above nominal on the downlink.

Based on the 900MHz uplink, a noise floor of -61dBm in a 100kHz bandwidth was used for the simulations.

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[4] FCC CFR 47 part 20.21 Signal Boosters, described further in Appendix D.1

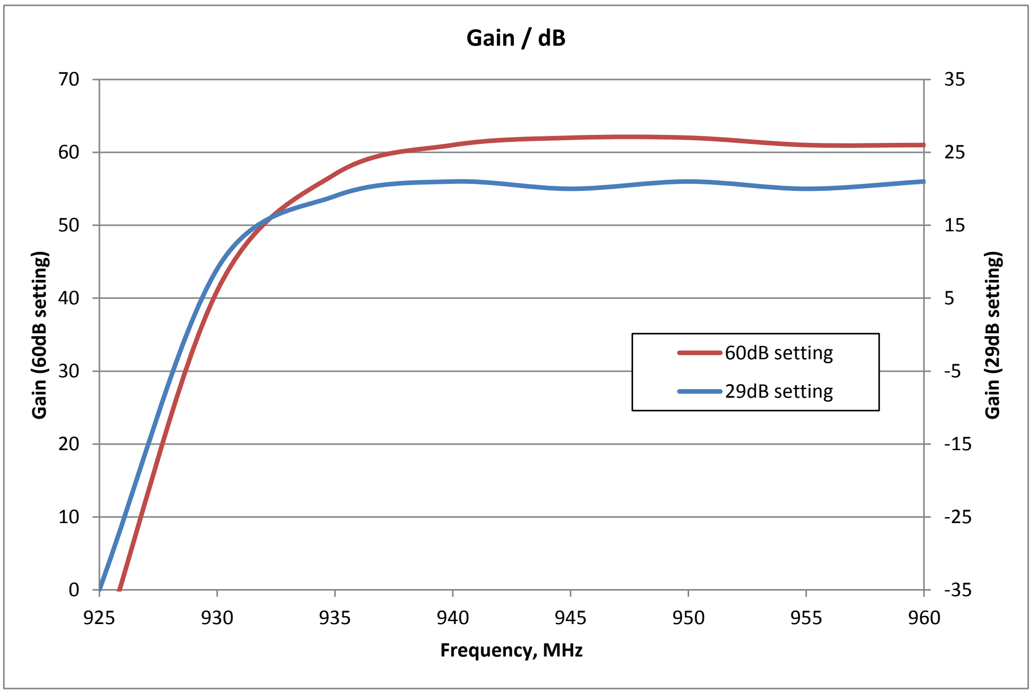

Figure 12. 900DL frequency response

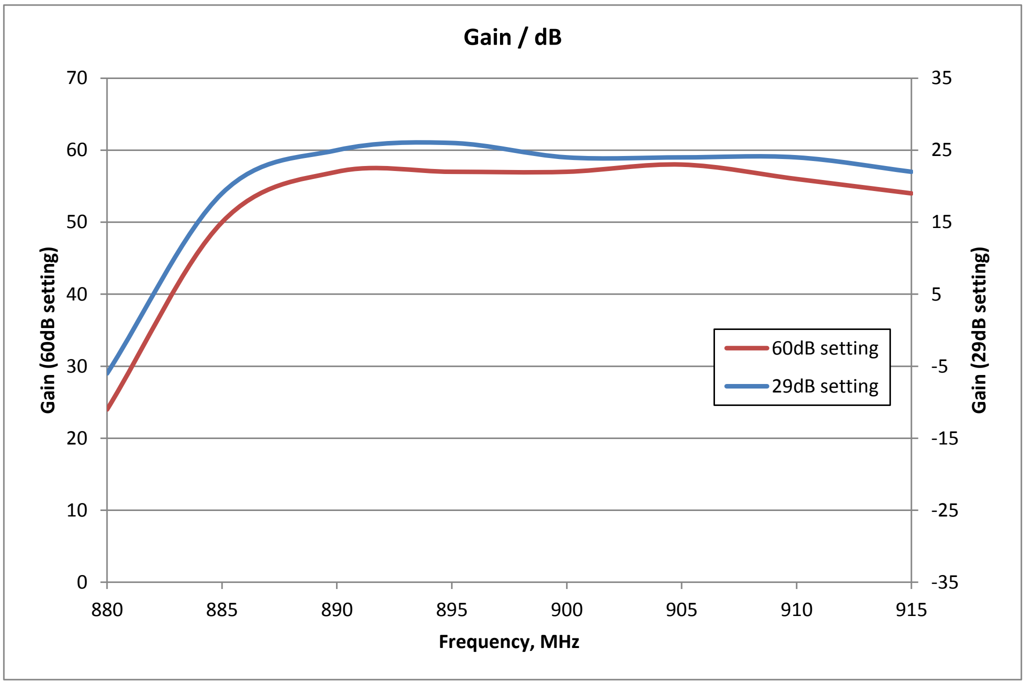

Figure 13. 900UL frequency response

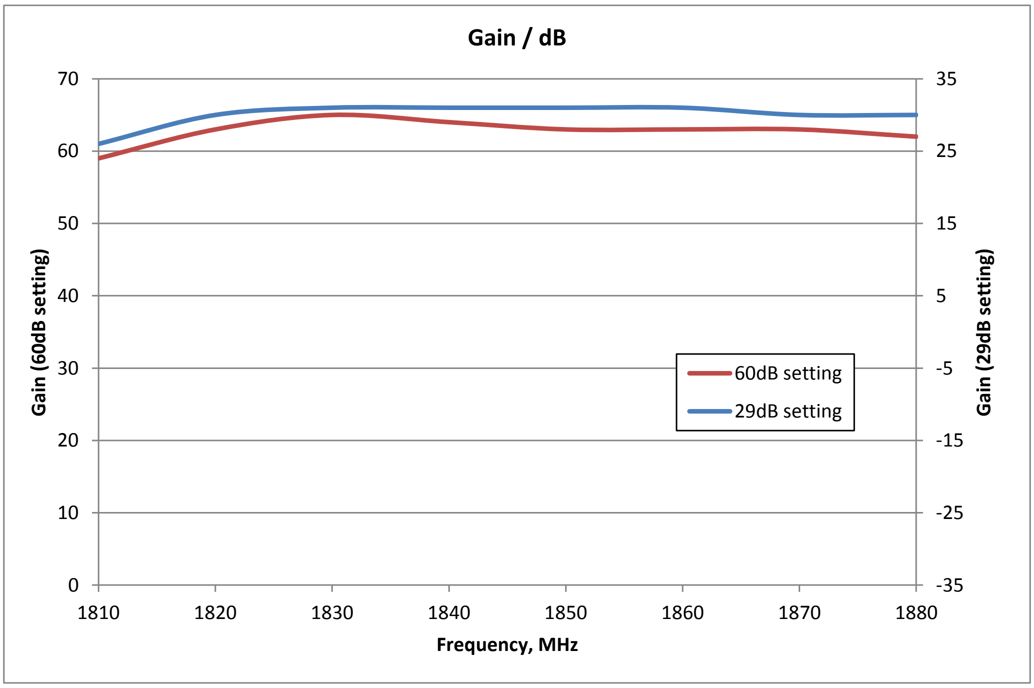

Figure 14. 1800DL frequency response

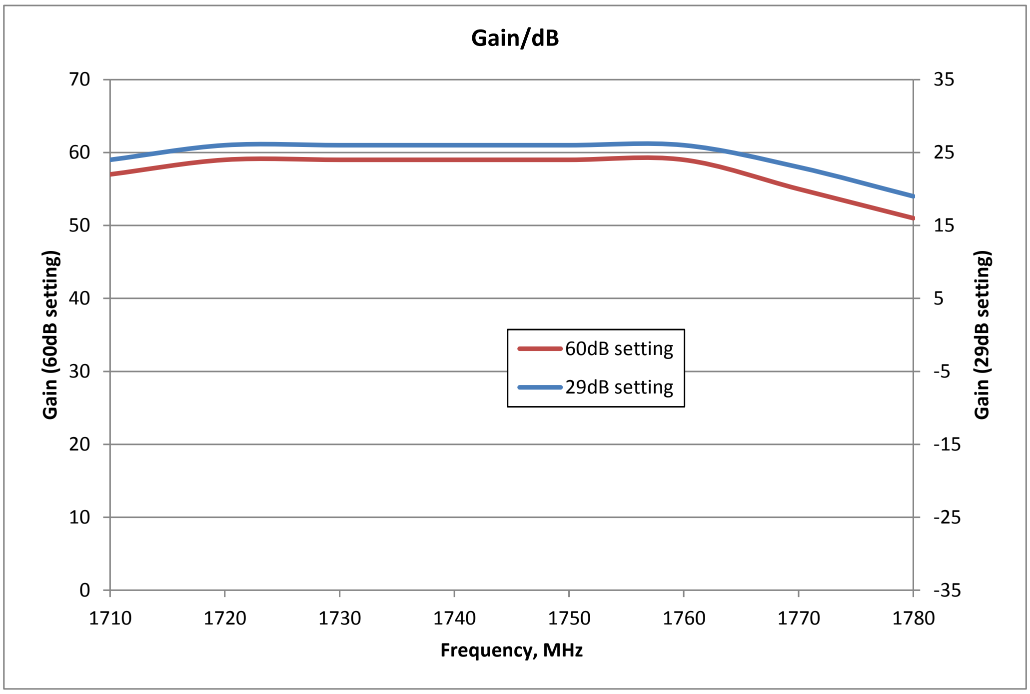

Figure 15. 1800UL frequency response

Maximum Output Power

A frequency in the middle of each of the four bands was selected and the input level increased until the output power started to compress. The compression points are shown in Table 4 below, the graphs from which the figures are derived are in Appendix B.1.2.

Table 4. Gain compression

Frequency band	Output power at 1dB compression, dBm
900MHz Downlink	+16
900MHz Uplink	+17
1800MHz Downlink	+14
1800MHz Uplink	+18

Harmonics and spurious emissions

The second harmonic was visible on each band, with the third harmonic also visible on the downlink bands. The levels varied but in some instances exceeded -50dBc.

There were no non-harmonic spurious emissions seen.

Distortion

The distortion to a QPSK signal at 270.8ksps (the GSM symbol rate) was measured for each of the four frequency bands. This was done at maximum gain with an input level at least 8dB below the compression points identified above. This was to identify the underlying distortion as distinct from compression at high signal levels.

The Error Vector Magnitude (EVM) was measured as 0.8% to 1.1% across the four bands. However there is 0.8% EVM when connecting the signal generator directly to the analyser. The EVM due to the repeater is therefore less than 1% in each case.

The adjacent channel power was measured on the spectrum analyser during the network tests (see section 4.2.2) by routing the mobile through the repeater and comparing the results with the non-repeater path. In view of the similar, low levels of EVM measured across the four bands, this test was conducted on the 900MHz uplink only. The mobile was in GSM mode and the repeater was at maximum gain.

The first two adjacent channels on either side of the wanted signal showed no difference between the results with and without the repeater. At the third adjacent channel and beyond, the repeater's power level stayed flat whereas the mobile's power continued to fall with increasing offset from the carrier frequency. This was due to the repeater's noise floor, no power increase in the adjacent channels was observed that appeared to be due to distortion.

Delay

The delay was measured to be 160ns on 900MHz DL and UL, 110ns on 1800MHz DL and UL. The measurement accuracy was estimated at ±20ns.

Stability

The repeater oscillated in each of the four bands when the attenuation in the feedback path was reduced sufficiently. There was no indication on the repeater itself of an unsafe condition.

4.2.2 Network Emulation

Using the test configuration shown in Figure 6 the impact of the repeater on a mobile in call was measured. The network emulator and mobile were set up to run a circuit switched voice call in GSM and 3G, and a high rate packet data channel in LTE. For the LTE connection the high rate data was in the downlink with handshaking in the uplink – the repeater was therefore causing errors by disrupting the handshaking process rather than the high rate data itself.

The sensitivity of the network emulator was significantly worse than that of a base station. Consequently the absolute figures for path loss that could be reached were not representative of those that would occur in a real network. Instead the difference between the path losses to the emulator from the mobile and from the repeater was recorded. This relative path loss was recorded at the point where a given criteria was exceeded, corresponding to a noticeable degradation of the signal from the mobile. The results are given in full in Appendix B.2. The conclusions in terms of the relative path losses are shown in Table 5.

Table 5. Path loss needed to interfere with call

Network type	Connection	Criteria	Relative path loss, dB
GSM 900MHz	Voice call, 9.6kbps	Call drop	73
UMTS 900MHz	Voice call, 12.2kbps	EVM exceeds spec limit	76
LTE 1800MHz	3.9Mbps DL data	5% BLER	34
LTE 1800MHz	3.9Mbps DL data	10 % BLER	33

As described above, there is very little distortion in the repeater. The EVM degradation was to the mobile's signal, which was not passing through the repeater, and was caused by the repeater's wideband noise floor.

4.2.3 The Effect on a Mobile Network

The relative path loss was translated into the effect on a mobile network by the following steps:

- Estimate maximum path loss to a mobile in the absence of interference, based on 3GPP standards and realistic equipment parameters
- Subtract the relative path loss figure from Table 5 to give the maximum path loss to the repeater
- Calculate the distance corresponding to these two path loss figures using the Extended Hata model

The results of this calculation are shown in Table 6.

Table 6. Interference radius calculated from lab test results

Network type	Connection	Cell radius, m	Repeater interferes within a range of, m
GSM 900MHz	Voice call, 9.6kbps	33,825	358
UMTS 900MHz	Voice call, 12.2kbps	33,825	290
LTE 1800MHz	3.9Mbps DL data	5,035	586
LTE 1800MHz	3.9Mbps DL data	4,716	545

It should be noted that the cell radius figures are the maximum in the absence of any interference. A real cellular network will have significantly smaller cell radii due to interference from various sources and the need to overlap cells to ensure coverage.

4.3 Simulations

SEAMCAT was used to simulate the effect of a repeater on the performance of a base station operating on a different frequency in the same band.

For all of the three technologies, we have simulated the interference from one GSM repeater in the UL against varying distances between a victim base station and the repeater as well as a typical range of repeater noise floor.

4.3.1 GSM

For GSM, output of the simulations considered is the probability of the signal to interference and noise ratio (SINR) being lower than 6dB. This is approximately the point at which a voice call would be dropped or blocked. Figure 16 shows the interference to a GSM base station from a repeater noise floor of -61dBm in a 100kHz bandwidth, as measured in section 4.2.1. Figure 17 shows the effect of varying that noise floor.

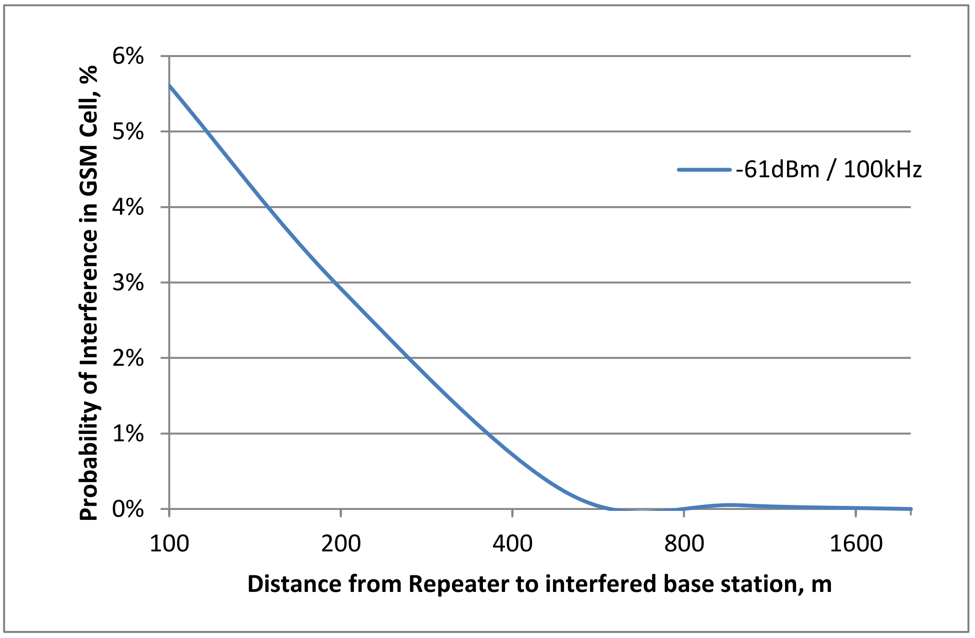

Figure 16. Interference to GSM cell vs repeater distance

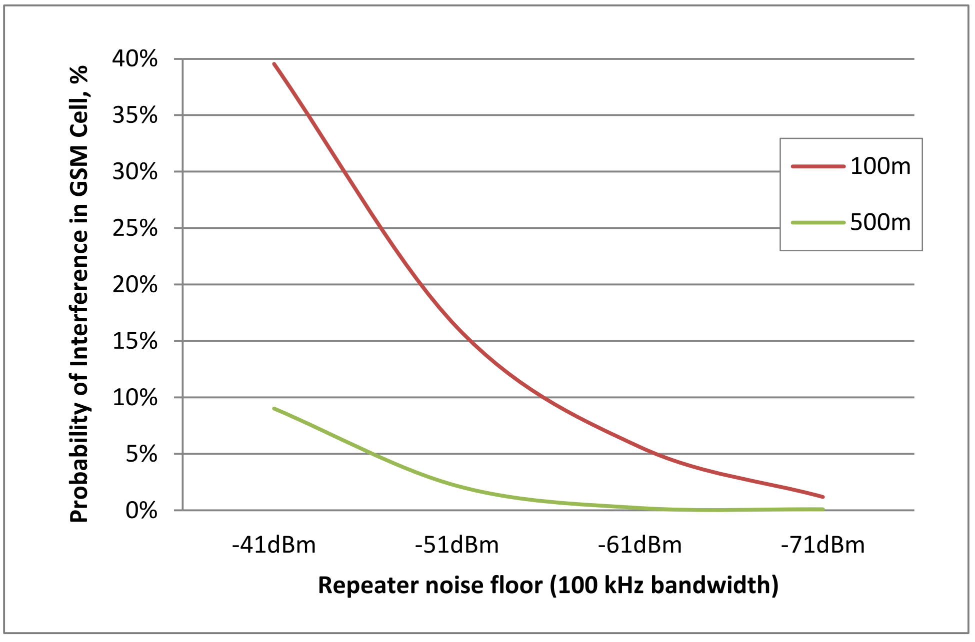

Figure 17. Interference to GSM cell vs repeater noise floor

4.3.2 3G

For 3G, the output of the simulations considered is capacity loss rate, i.e. the reduction in the number of active users. This measure is used in preference to dropped calls due to the 'cell breathing' effect in a CDMA system. The effect is that mobiles with the noisiest signal are handed over to neighbouring cells and the cell's coverage area shrinks or 'breathes'. To quantify this, a threshold of 3dB Ec/Ior is used for initiating a cell handover. Figure 18 shows the interference to a UMTS base station from a repeater noise floor of -61dBm in a 100kHz bandwidth, as measured in section 4.2.1. Figure 19 shows the effect of varying that noise floor.

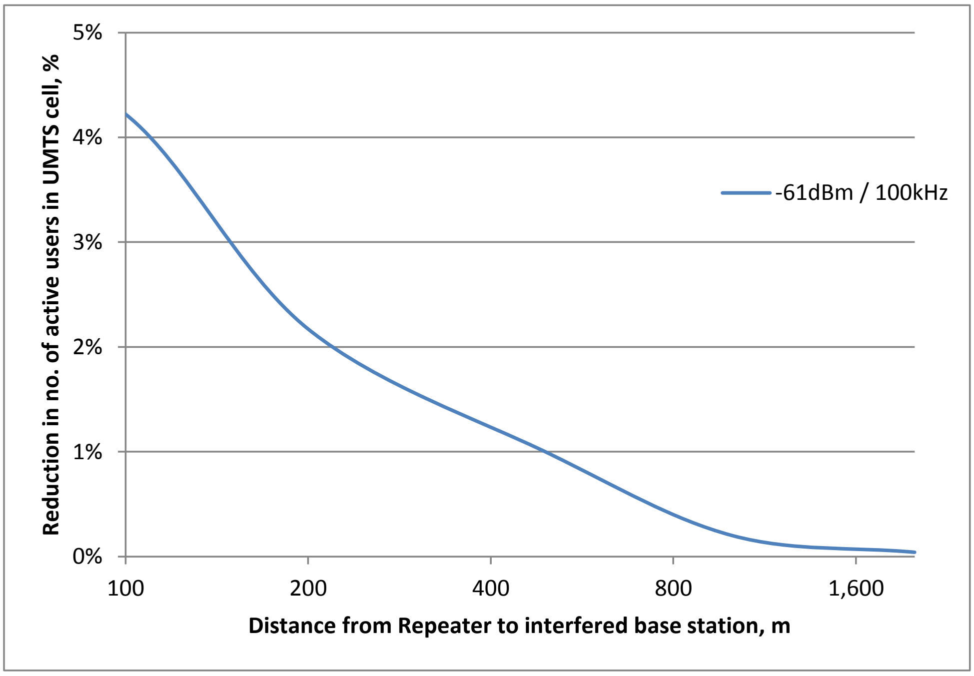

Figure 18. Interference to 3G cell vs repeater distance

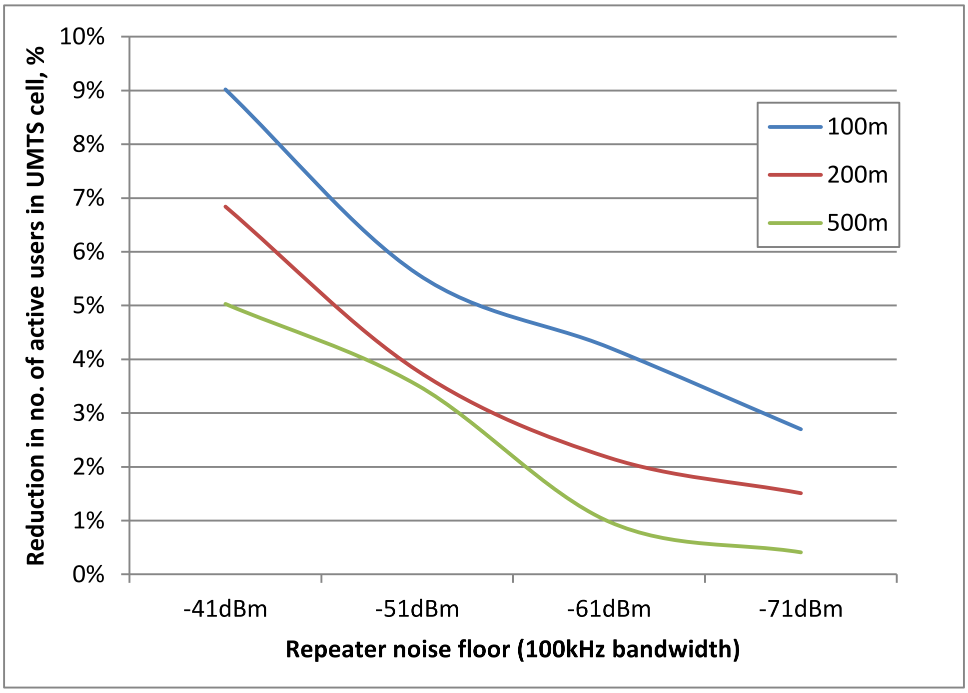

Figure 19. Interference to 3G cell vs repeater noise floor

4.3.3 LTE

The output of the simulations considered is the loss of bit rate to the users due to repeater interference. This is expressed as a percentage of the bit rate available without interference. Figure 20 shows the interference to an LTE base station from a repeater noise floor of -61dBm in a 100kHz bandwidth, as measured in section 4.2.1. Figure 17 shows the effect of varying that noise floor.

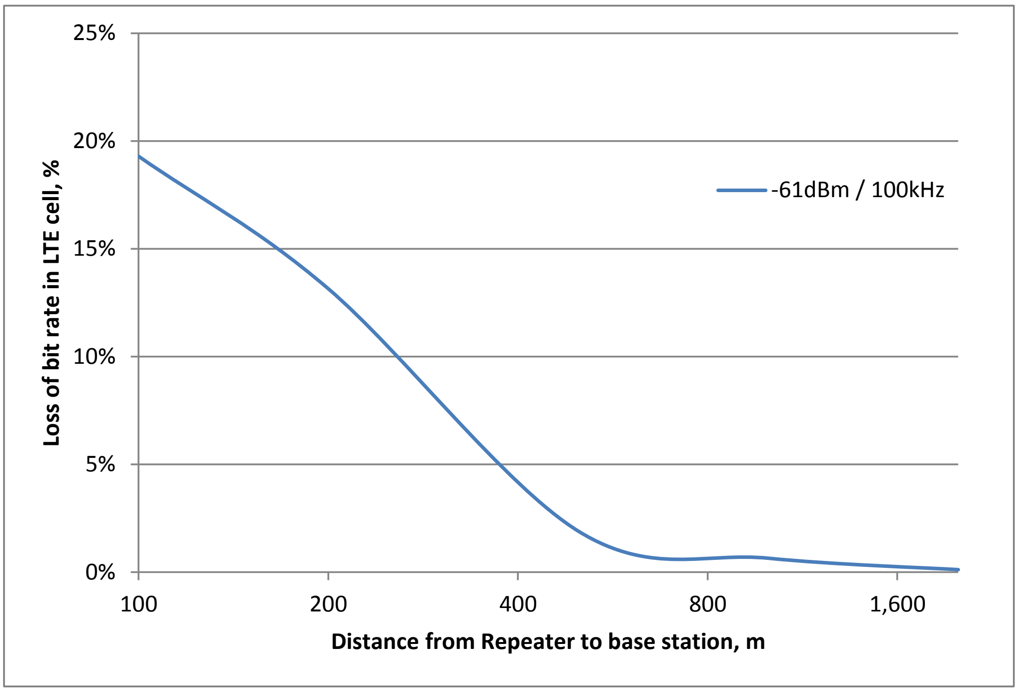

Figure 20. Interference to LTE cell vs repeater distance

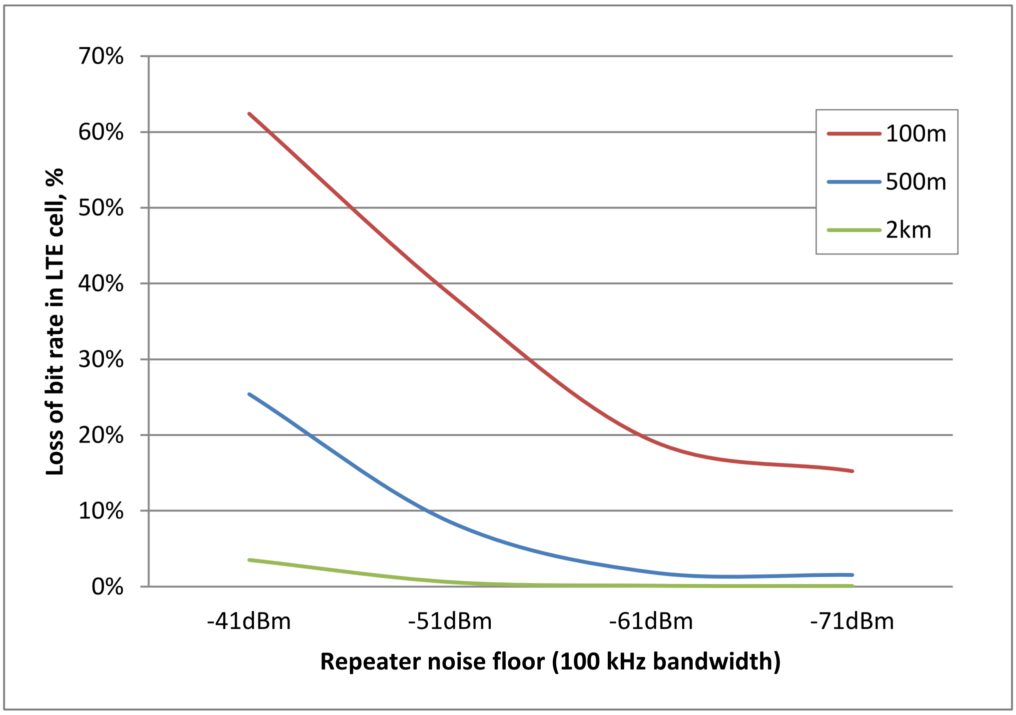

Figure 21. Interference to LTE cell vs repeater noise floor

4.4 Interpreting the Results

This section collates the test and simulation results and relates them to the effect of a repeater on a real network.

4.4.1 Range of Repeater

GSM

Using the noise floor measured on the example repeater, simulations show that the interference exceeds 1% call drop rate when the repeater is just less than 400m from the base station. This is close to the figure of 358m calculated from the network test results.

3G

The simulations of 3G show similar trends to GSM. The interference exceeds 1% capacity loss when the repeater is within about 500m of the base station. The range of 290m calculated from the network test results, gives just less than 2% capacity loss in the simulations.

LTE

The simulations of LTE show similar trends to GSM and 3G. Different criteria were used for packet data compared to voice calls. The radius at which 5% BER in LTE occurred was just less than 400m. It is notable that this is very similar to the radius for 1% call drop in GSM. The figure calculated from the network tests at 1800MHz was 586m for 5% BLER.

4.4.2 Effect of Noise Level

Reducing the absolute noise floor of the repeater by 10dB brings the 400m distance for GSM down to around 100m. The channel-selecting repeaters currently available show that a 10dB reduction in noise floor is realistic for an 'Off' channel. Further reductions may well be feasible with different designs. Simulation of a reduced noise level has less effect on LTE than on GSM or 3G.

The FCC specification for Consumer Signal Boosters defines a maximum noise power in absolute terms and as a function of received strength on the downlink. For the 900MHz band a fixed installation would have a maximum noise power of -53dBm / 100kHz when the signal level received on the downlink is -60dBm or less. For each 1dB that the downlink level rises above -60dBm, the noise floor is required to reduce by 1dB. Using the same Hata propagation model, as for other parts of this analysis, this means the repeater's permitted noise level would start to fall when it came within about 2km of a macro base station. It can be seen from the graphs of section 4.3 that there is negligible interference at this range. This implies that a repeater meeting the FCC noise limits should cause few if any problems.

The combined effect of multiple repeaters will be to raise the noise floor. However the effect of multiple randomly distributed repeaters is dominated by the effect of the closest device, assuming they all have approximately equal transmitted noise powers. The results above are therefore likely to be slightly worse, but not massively so, in practice when the distance from the nearest repeater to the base station is used. In this context it should be noted that one of the mitigation features, switching off the uplink when not in use, relates specifically to reducing the combined effect of multiple repeaters.

5 CONCLUSIONS

It is easy to buy a repeater online and there is lots of choice in models and suppliers. Most repeaters are fairly cheap but limited in features that would reduce interference. More sophisticated models are available that include good anti-interference measures - these devices tend to be more expensive.

The dominant interference effect is desensitisation of the base station by the noise floor of the repeater's uplink transmission. Professionally designed and approved repeater installations are used by the operators themselves, which suggests repeaters are not inherently a problem. Problems come from poor repeater design and inexpertly installed repeaters – both by consumers and untrained 'professionals'.

Several technical features that mitigate interference have been found in repeater designs:

- Channel selectivity – only transmitting on the relevant uplink channel(s)
- Switching off the uplink when not in use to reduce the combined noise level where multiple repeaters are installed in the same cell
- Intelligent gain control to reduce uplink power and noise when close to the base station. This needs to be implemented correctly to achieve good noise reduction. It is also complicated where multiple operators with separate base station sites are required, leading to the channel selectivity feature
- Anti-oscillation measures

The 'Near-far' problem could be mitigated by requiring the use of directional antennas for the network side of the repeater. This ensures that the signal power and the noise from repeater are directed at the distant base station. Directional antennas are readily available and are supplied with some repeaters. However enforcing their use, and ensuring their correct alignment in consumer installations, could be difficult. Their use is complicated by installations that intend to use multiple operators' base station sites. The gain of directional antennas may also exacerbate the problem where there is a low path loss from the repeater to the wanted base station.

Consideration has also been given to procedural measures to avoid interference. The FCC process in particular appears to have addressed all the main concerns, which include:

- The operators have knowledge of newly installed repeaters
- A certification specification for self-installed devices that minimises the risk of interference
- A licensed installer is required for any uncertified repeater.

APPENDICES

A NOISE IN RADIO SYSTEMS

One of the limiting factors in any radio system is the level of electronic noise. This is generated in any circuit by basic physical effects. The noise is "white" at all frequencies of interest i.e. its power is constant with frequency and proportional to the bandwidth being measured.

In the case of an amplifier, such as those in a repeater, the noise at the input is amplified along with the wanted signal. The amplifier itself also adds some noise. The internal noise is usually quoted as the Noise Figure, which is the ratio of SNR at the input to SNR at the output, expressed in dB.

Assuming there are no external noise sources, the thermal noise power at the input, Pin, is given by:

$$Pin = k\ T\ B$$

Where k is Boltzmann's constant, T is the absolute temperature and B is the bandwidth. At room temperatures this gives a power of -174dBm/Hz. The bandwidth is expressed in dB as

$$10.log10(BW)$$

This is then amplified by the gain, G, and the amplifier's noise figure, NF, is added. The noise power at the output, Pout, is:

$$Pout = -174 + 10.log10(BW) + G + NF$$

As an example, GSM receivers have an effective bandwidth of approximately 200kHz, or 53dBHz. The repeater that was tested had a noise figure of around 6dB average at maximum gain, and that gain was about 60dB in the uplink. The output noise power in this case is:

$$Pout = -174 + 53 + 60 + 6dBm = -55dBm$$

The ETSI specified reference sensitivity of a GSM base station is -104dBm. The noise power from the repeater, as seen by the base station, will be above this limit if the path loss between the repeater and base station is less than 49dB.

B TEST RESULTS

The results below are taken from testing one example unit of a low-cost dual-band consumer repeater.

B.1 RF Characterisation

B.1.1 Gain, Frequency Response, Noise

Table 7. 900DL gain and noise

Frequency, MHz	Gain at minimum gain, dB	Gain at maximum gain, dB	Noise Floor at maximum gain, dBm/100kHz
925	-35	-9	Below analyser noise floor
930	9	41	-65
935	19	57	-59
940	21	61	-57
945	20	62	-57
950	21	62	-56
955	20	61	-56
960	21	61	-56

Table 8. 900UL gain and noise

Frequency, MHz	Gain at minimum gain, dB	Gain at maximum gain, dB	Noise Floor at maximum gain, dBm/100kHz
880	-6	24	Below analyser noise floor
885	19	50	-66
890	25	57	-62
895	26	57	-62
900	24	57	-62
905	24	58	-61
910	24	56	-61
915	22	54	-63

Table 9. 1800DL gain and noise

Frequency, MHz	Gain at minimum gain, dB	Gain at maximum gain, dB	Noise Floor at maximum gain, dBm/100kHz
1810	26	59	-59
1820	30	63	-57
1830	31	65	-57
1840	31	64	-56
1850	31	63	-57
1860	31	63	-56
1870	30	63	-57
1880	30	62	-57

Table 10. 1800UL gain and noise

Frequency, MHz	Gain at minimum gain, dB	Gain at maximum gain, dB	Noise Floor at maximum gain, dBm/100kHz
1710	24	57	-61
1720	26	59	-60
1730	26	59	-59
1740	26	59	-59
1750	26	59	-59
1760	26	59	-59
1770	23	55	-62
1780	19	51	-64

B.1.2 Maximum Power

The output power of the 900MHz downlink at 1dB compression was +16dBm, as shown in Figure 22.

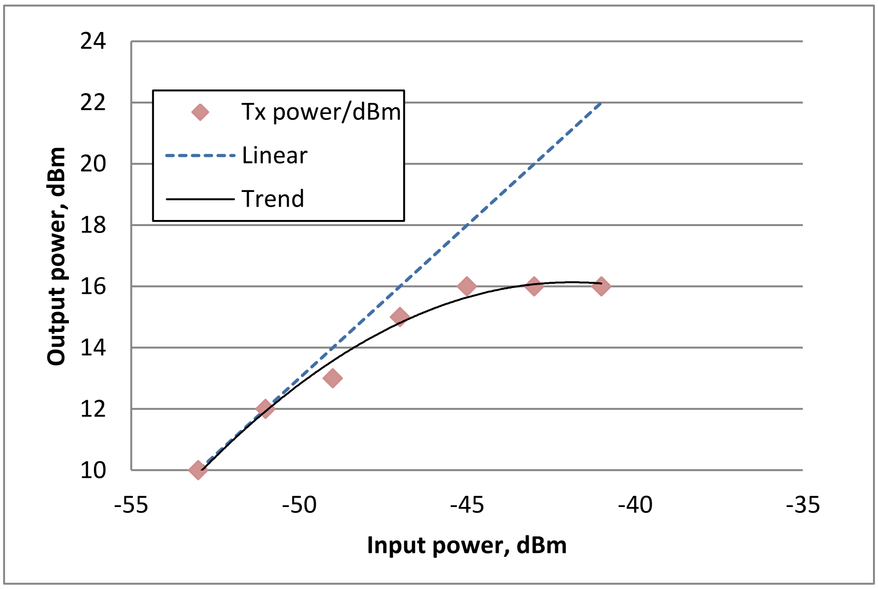

Figure 22. 900DL gain compression

The output power of the 900MHz uplink at 1dB compression was +17dBm, as shown in Figure 23.

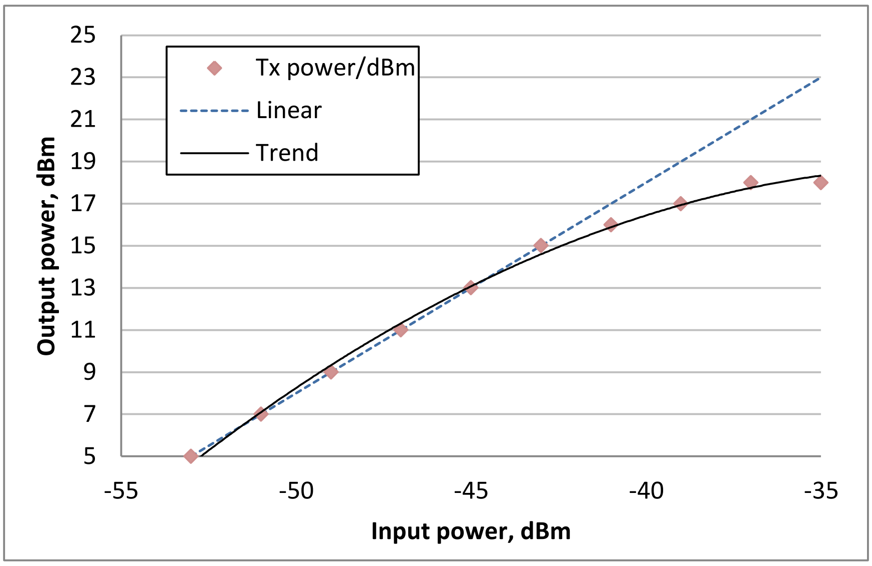

Figure 23. 900UL gain compression

The output power of the 1800MHz downlink at 1dB compression was +14dBm, as shown in Figure 24.

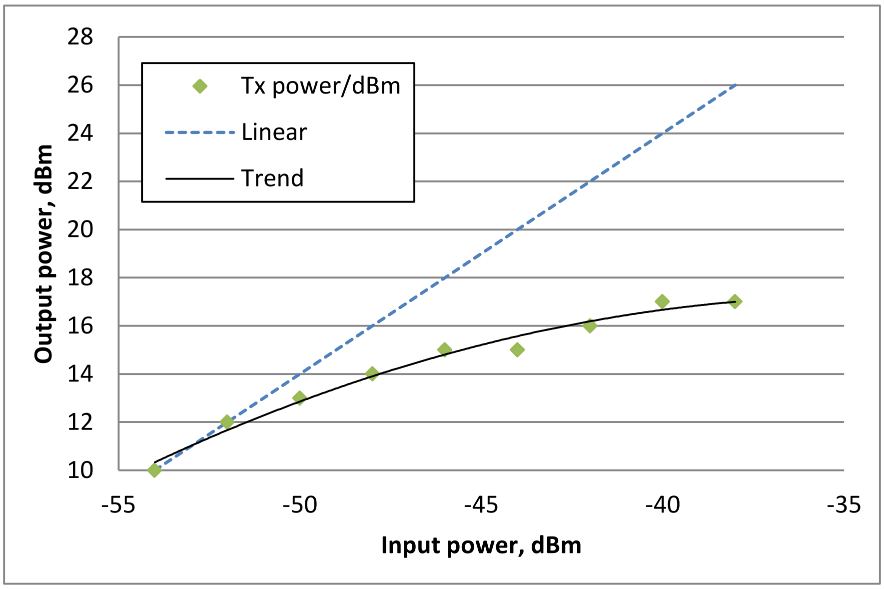

Figure 24. 1800DL gain compression

The output power of the 1800MHz uplink at 1dB compression was +18dBm, as shown in Figure 25.

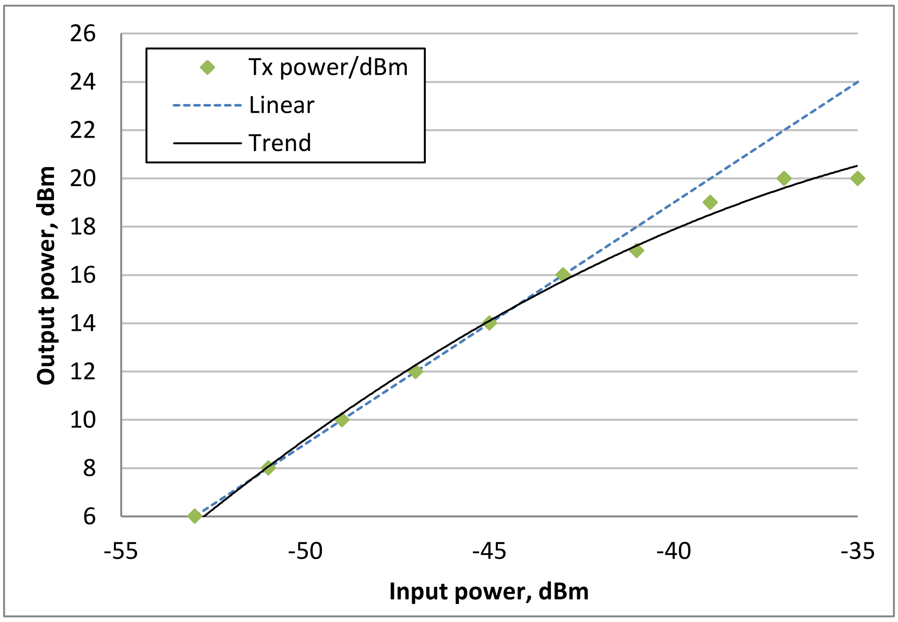

Figure 25. 1800UL gain compression

B.1.3 Harmonics and spurious emissions

Table 11. Harmonic emissions

Frequency band	Input Frequency, MHz	Harmonic Frequency, MHz	Level, dBc
900MHz Downlink	950	1900 (2nd)	-63
	950	2850 (3rd)	-74

900MHz Uplink	885	1770 (2nd)	-43
1800MHz Downlink	1850	3700 (2nd)	-63
	1850	5550 (3rd)	-46
1800MHz Uplink	1740	3480 (2nd)	-72

Note that the measurement network was uncalibrated at harmonic frequencies so the levels given are approximate.

No other spurious emissions were observed.

B.1.4 Distortion

Table 12. Distortion below compression point

Frequency band	Measured, %	Signal Generator, %	Repeater, %
900MHz Downlink	1.0	0.8	0.6
900MHz Uplink	0.8	0.8	-
1800MHz Downlink	1.1	0.8	0.8
1800MHz Uplink	0.9	0.8	0.4

Table 13. Adjacent channel power

Configuration	-3 chan.	-2 chan.	-1chan.	+1 chan.	+2 chan.	+3 chan.	
Mobile only	-71	-61	-17	-16	-60	-70	dBc
Via repeater	-69	-61	-17	-16	-60	-68	dBc

B.1.5 Delay

Table 14. One-way delay

Frequency band	Delay, ns
900MHz Downlink	160
900MHz Uplink	160
1800MHz Downlink	110
1800MHz Uplink	110

Measurement accuracy ±20ns

B.2 Network Emulation

The configuration of the test network is shown in Figure 26. This was common for all three standards with the settings varied as described below.

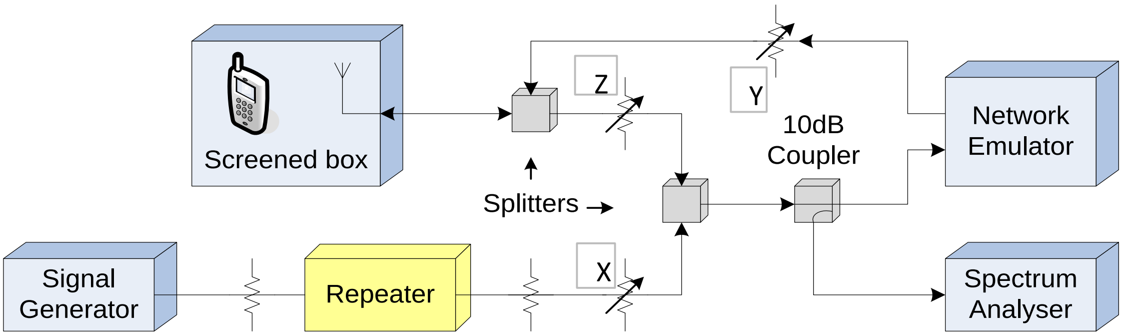

Figure 26. Network emulation test configuration

The mobile was a Samsung Galaxy S3 with a Test SIM to match the network emulator. The signal generator was set to emulate a GSM mobile in the same band as the network but at a different frequency. The signal generator was set to a level that was below the compression point of the repeater.

Three variable attenuators X, Y and Z were used to vary the path losses. X was for the repeater uplink, Y was for the mobile downlink, and Z was for the mobile uplink. Y was set to give a signal at the mobile that was sufficient to give an error-free downlink but low enough not to inject excess noise into the system.

The relationship between X and Z was the output of the tests. The criteria at which the repeater noise was judged to have interfered with the network is explained in section 3.2.2 Network Emulation. Z was varied in 5dB steps, and at each step X was varied to find the point at which interference occurred. The results were plotted on a graph and a trend line used to find the value of Z corresponding to 0dB on X.

Finally the path losses with X and Z both set to 0dB was added to give the actual path losses from repeater and mobile respectively.

B.2.1 GSM

The 900MHz band was used for the GSM tests. The results are shown in Figure 27.

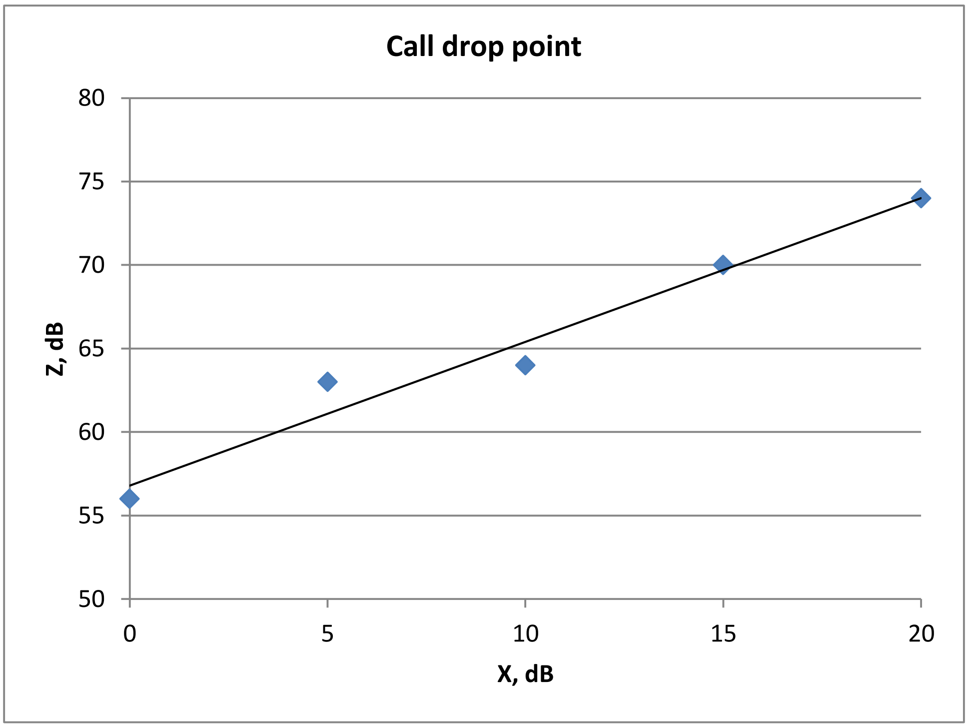

Figure 27. Attenuator settings for GSM interference

The intercept point for the trend line was Z = 56.8dB. The fixed path losses were 19.7dB and 35.5dB for X and Z respectively. This means that the relative path loss between mobile and repeater at call drop was (56.8 + 35.5 – 19.7) = 72.6dB, rounded to 73dB.

B.2.2 3G

The 900MHz band was used for the 3G tests. The results are shown in Figure 28.

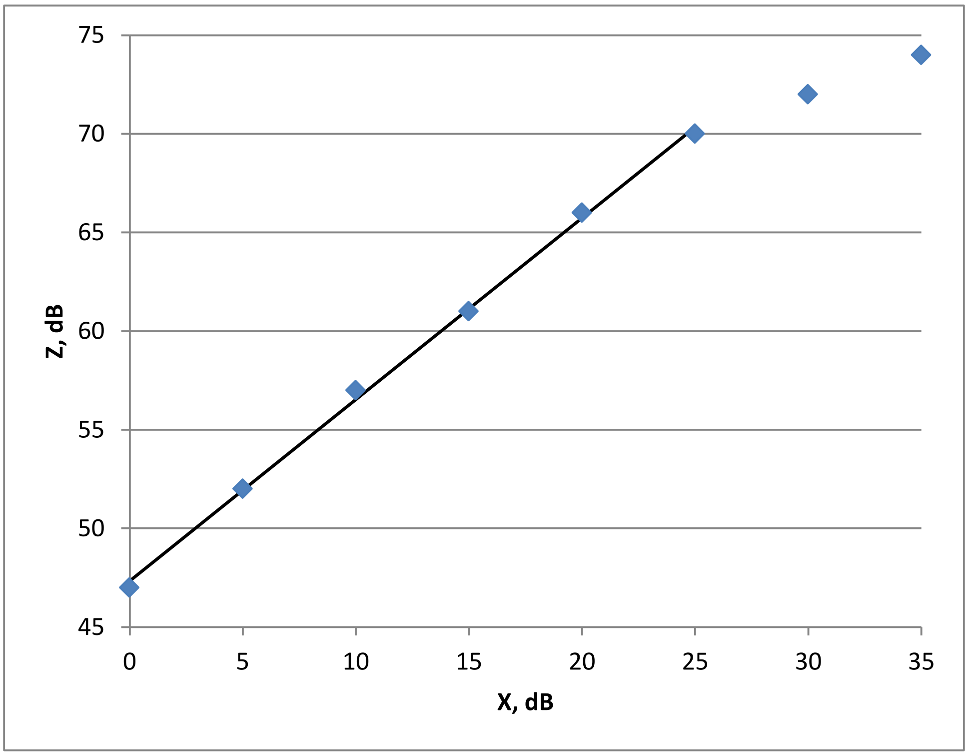

Figure 28. Attenuator settings for 3G interference

The intercept point for the trend line was Z = 47.3dB. The fixed path losses were 19.7dB and 48.7dB for X and Z respectively. This means that the relative path loss between mobile and repeater at call drop was (47.3 + 48.7 – 19.7) = 76.3dB, rounded to 76dB.

B.2.3 LTE

The 1800MHz band was used for the LTE tests. The results are shown in Figure 29.

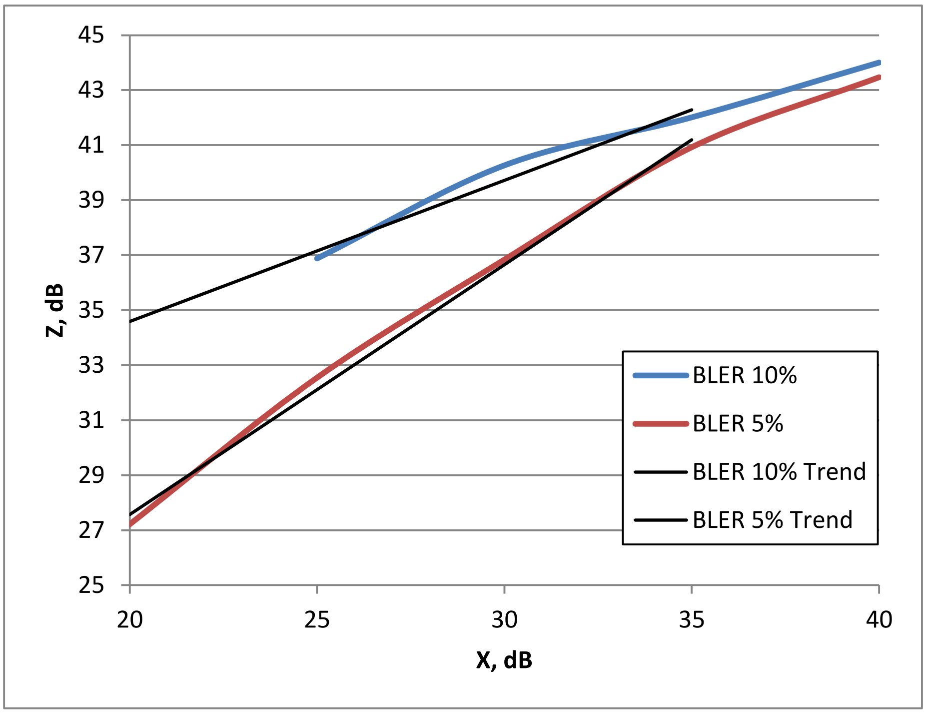

Figure 29. Attenuator settings for LTE interference

Unlike the GSM and 3G results it is noticeable that the two lines converge and that the BLER 10% curve in particular has a much greater sensitivity to X than to Z. The point on the curve at which the result is taken is therefore important. The points at which X = 35dB were chosen as these represented the mobile at around 9dB above its sensitivity limit, equivalent to being in an area of weak but still useable coverage. It is these mobiles that would be most vulnerable to interference with the network.

The points on the trend lines for X = 35dB were Z = 42.3dB (BLER 10%) and 41.2dB (BLER 5%).

The fixed path losses were 22.0dB and 48.7dB for X and Z respectively. This means that the relative path losses between mobile and repeater were:

- 34.0dB (BLER 10%), rounded to 34dB
- 32.9dB (BLER 5%), rounded to 33dB.

C SIMULATION PARAMETERS AND RESULTS

The terms ‘Interfering’ and ‘Victim’ are used to refer to the relevant sections of the SEAMCAT input screens. They are not used as an indication of the results of the simulations.

C.1 Input Parameters

C.1.1 Repeater (Interfering Transmitter)

The repeater is simulated as a single channel GSM transmission plus a wideband noise floor. The Emission Power and Emission Mask refer to the GSM signal, the Emission Floor refers to the noise.

Table 15. General settings - repeater

Parameter	Setting
Interfering Transmitter to Victim Base Station Distance	50, 100, 200, 500, 1000, 2000m
Propagation Model	Extended Hata
Environment	Rural outdoor
Emission Power	+18dBm
Emission Floor	-41, -51, -61, -71 dBm / 100 kHz
Antenna Gain	0 dBi
Operating Frequency	900 MHz

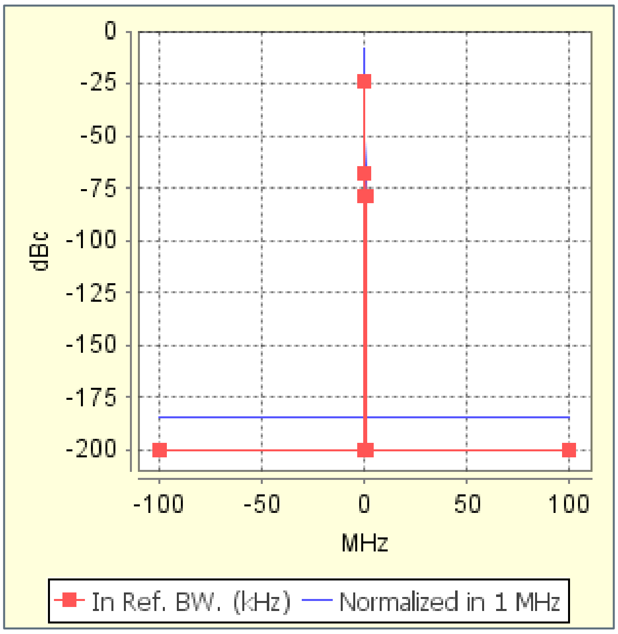

Figure 30. Emission mask - repeater

C.1.2 GSM Victim Base Station

Table 16. General settings – GSM network

Parameter	Setting
Noise Floor	-110 dBm
Sensitivity	-103 dBm
Reception Bandwidth	200 kHz
Receiver Noise Figure	4 dB
C/I	9 dB
C/(I+N)	6 dB
Cell Radius	15 km
Operation Frequency	905 MHz
Mobile Antenna Height	1.5m
Mobile Antenna Gain	0dBi
Base Station Antenna Height	30m
Base Station Antenna Gain	15 dBi
Operating Frequency	905 MHz

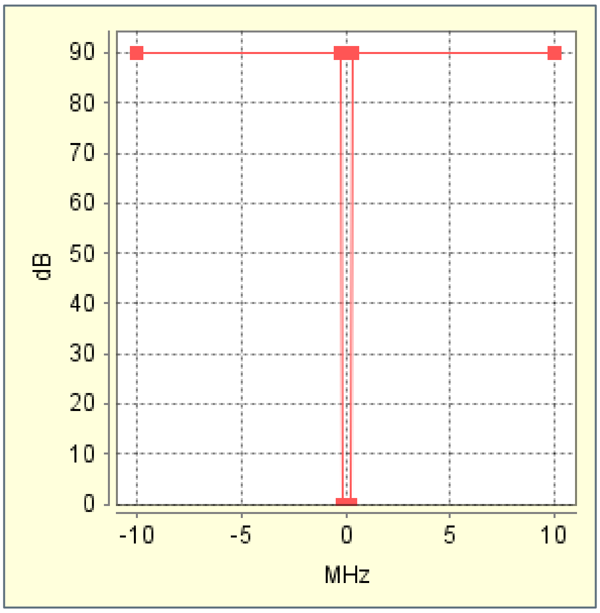

Figure 31. GSM receiver blocking mask

C.1.3 3G Victim Base Station

Table 17. General settings – 3G network

Parameter	Setting
Handover Margin	3 dB
Call Drop Threshold	3 dB
Voice Bit Rate	12.2 kbps
Minimum Coupling Loss	30 dB
System Bandwidth	3.84 MHz
Receiver Noise Figure	4 dB
MS Maximum Transmit Power	21 dBm
MS Power Control Range	70 dB
Users per Base Station	20
Cell Radius	15 km
Mobile Antenna Height	1.5m
Mobile Antenna Gain	0dBi
Base Station Antenna Height	30m
Base Station Antenna Gain	15 dBi
Operating Frequency	905 MHz

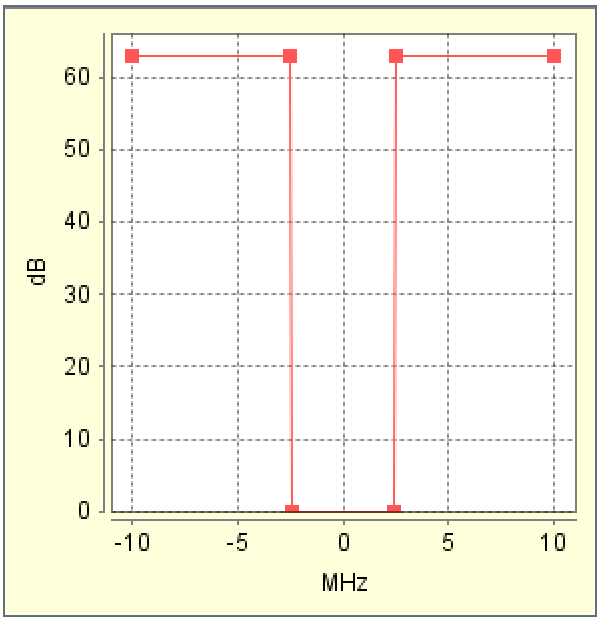

Figure 32. 3G receiver blocking mask

C.1.4 LTE Victim Base Station

Table 18. General settings – LTE network

Parameter	Setting
SINR Minimum	-20 dBm
Subcarriers per Base Station	25
Subcarriers per Mobile	5
Minimum Coupling Loss	30 dB
System Bandwidth	5 MHz
Receiver Noise Figure	4 dB
Bandwidth of Resource Block	180 kHz
MS Maximum Transmit Power	24 dBm
Users per Base Station	20
Cell Radius	15 km
Mobile Antenna Height	1.5m
Mobile Antenna Gain	0dBi
Base Station Antenna Height	30m
Base Station Antenna Gain	15 dBi

Operating Frequency	905 MHz

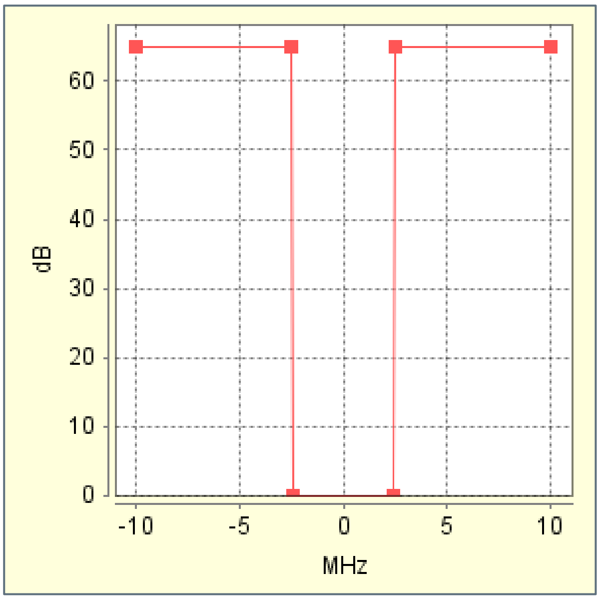

Figure 33. LTE receiver blocking mask

C.2 Results

C.2.1 GSM Network

Table 19. Effect of distance between repeater and GSM base station

Repeater to Base Station range, m	Probability of Interference
50	4.3%
100	5.6%
200	2.9%
500	0.2%
1000	0.1%
2000	0%

Repeater noise floor at -61dBm/100kHz

Table 20. Effect of repeater noise floor on GSM base station

Noise Floor, dBm/100kHz	Repeater to base station range		
	50m	100m	500m
-41	52.5%	39.6%	9.0%

-51	21.0%	21.0%	2.2%
-61	4.3%	4.3%	0.2%
-71	0.3%	0.3%	0.1%

C.2.2 3G Network

Table 21. Effect of distance between repeater and 3G base station

Repeater to Base Station range, m	Probability of Interference
50	4.9%
100	4.2%
200	2.2%
500	0.98%
1000	0.20%
2000	0.04%

Repeater noise floor at -61dBm/100kHz

Table 22. Effect of repeater noise floor on 3G base station

Noise Floor, dBm/100kHz	Repeater to base station range		
	100m	200m	500m
-41	9.0%	6.8%	5.0%
-51	5.6%	3.8%	3.5%
-61	4.2%	2.2%	0.98%
-71	2.7%	1.5%	0.41%

C.2.3 LTE Network

Table 23. Effect of distance between repeater and LTE base station

Repeater to Base Station range, m	Loss of bit rate
50	22.4%
100	19.3%
200	13.2%
500	1.9%

1000	0.6%
2000	0.1%

Repeater noise floor at -61dBm/100kHz

Table 24. Effect of repeater noise floor on LTE base station

Noise Floor, dBm/100kHz	Repeater to base station range		
	50m	**100m**	**500m**
-41	87.9%	39.6%	25.4%
-51	54.3%	21.0%	8.5%
-61	22.4%	4.3%	1.9%
-71	14.4%	0.3%	1.5%

D REGULATORY POSITION IN OTHER COUNTRIES

The problem of interference to mobile networks from repeaters installed independently of the operators has been experienced in other countries. We understand the current position of regulators in three of these countries is as described below:

D.1 USA

The FCC introduced rules[5] for repeaters that came into effect on 1st March 2014. There are a large number of legacy repeaters that were installed before these rules came into effect. We understand that the rules were introduced in response to problems with interference from these earlier repeaters.

The essence of the rules is:

- Consumers may buy, self-install and use consumer repeaters subject to three main conditions:
  - The consumer registers the repeater with their network operator before switching it on
  - They must shut down the repeater if an operator complains of interference
  - The repeater must comply with the FCC "Consumer Signal Booster" specification
- The Consumer Signal Booster specification has a number of anti-interference measures including:
  - Detection and prevention of oscillations
  - Shutting down the repeater if it is near a base station
  - Shutting down the uplink if there is no mobile using the repeater
  - Limits on the transmitter power, noise floor, gain, asymmetry of uplink and downlink, out-of-band emissions and intermodulation
- Repeaters that do not comply with the Consumer specification are classified as an "Industrial Signal Booster" and must be installed by an FCC-licensed installer
- Consumer repeaters may be installed in fixed locations or in vehicles

It is not known what the compliance rate is for the initial registration, or for updating that registration if the repeater is relocated.

D.2 Germany

The law in Germany requires licences to transmit and has fines for non-compliance[6]. The regulator, Bundesnetzagentur (BNetzA), won a court case[7] in 2013 against Haider Telekom who had been supplying and installing repeaters. The court ruling said that repeaters cannot be installed or operated without the permission of the frequency licence holders, i.e. the mobile operators.

D.3 Australia

The Australian regulator, ACMA, has a position illustrated by this excerpt from their website[8]:

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5 FCC CFR 47 part 20.21 Signal Boosters

6 dejure.org/gesetze/TKG/55.html and dejure.org/gesetze/TKG/149.html (in German)

7 www.golem.de/news/verbot-freier-mobilfunk-repeater-tausende-anlagen-in-deutschland-betroffen-1309-101730.html (in German)

8 www.acma.gov.au/theACMA/mobile-phone-repeaters-information-for-consumers

A person must not operate or possess a radiocommunications device, unless that person is authorised under either a spectrum, apparatus or class licence.

A mobile phone repeater operates within apparatus or spectrum licensed radio frequency bands licensed to mobile phone carriers. As such, to operate this device, you will require carrier permission under a third party arrangement.

It is illegal to operate a repeater without carrier permission because this device has the capacity to cause substantial interference to the mobile network. This can occur because the device is not coordinated with other radiocommunications infrastructure in the mobile network.

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