Low-power concurrent use in the spectrum bands 1781.7 – 1785 MHz paired with 1876.7 – 1880 MHz

Interference scenarios, coordination between licensees and power limits

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Contents

Section 1

Summary

This technical study ("Technical Study") has been prepared by Ofcom, in connection with the proposed award of wireless telegraphy licences to use the spectrum bands 1781.7 – 1785 MHz paired with 1876.7 – 1880 MHz (the “Spectrum Bands”). It is issued in support of, and should be read together with, the Ofcom Consultation Document "Award of available spectrum: 1781.7-1785 MHz paired with 1876.7-1880 MHz" published on 28 July 2005 ("Consultation Document"). Terms and expressions used in this Technical Study are as defined in the Consultation Document.

The Technical Study is intended solely as a means for Ofcom to consider the viability of offering concurrent low power licences to use the Spectrum Bands and the development of technical conditions for inclusion in the licences. It is being made available for information purposes only. It is made available on the express understanding that it will only be used for the sole purpose of assisting in reviewing and responding to the Consultation Document, and not in assessing whether to participate in the proposed award of licences to use the Spectrum Bands. The Technical Study is not intended to form any part of the basis of any investment decision or other evaluation or any decision to participate in the proposed award of licences to use the Spectrum Bands and should not be considered as a recommendation by Ofcom or any of its advisers to do so. Any party considering participating in the proposed award of licences to use the Spectrum Bands must make its own independent assessment of the technical viability of using the Spectrum Bands and the potential value of a licence to use the Spectrum Bands after making such investigation as it may deem necessary in order to determine whether to participate. All information contained in this Technical Study is subject to updating, modification and amendment.

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Coverage and Capacity

This analysis confirms that a low power system based on GSM pico cells operating at the 23dBm power level can provide coverage in an example multi-storey office scenario. Two pico cells per floor would meet the coverage requirements in the example 50m × 120m office building. For a population of 300 people per floor, the two pico cells would also meet the traffic demand.

A seven-floor frequency re-use provides call success probability above 97% across the 50m range of the pico cell. For six-floor re-use the call success probability drops to 94% at the edge of the cell.

Coordination between neighbouring buildings in the commercial environment

A probabilistic analysis of interference between neighbouring office buildings with indoor GSM pico cells operating on the same radio frequency indicates that a 97% probability of call success inside each office could be achieved with 550m separation between buildings if there were no obstructions between them. For a building separation of 150m the probability of call success is achieved is better than 90%. We conclude that coordination is necessary.

We conclude that it is possible to serve users up to 40m within a building using an external base station with a power limit of 23dBm. However, to penetrate to users 50 meters within a building would require a higher power (30dBm would be needed to give a reasonable separation between the base station and building).

An outdoor micro cell could cause interference to an in-building pico cell system. At 3km a 23dBm micro cell reduces the call success probability on the pico cell system below 90% while a separation of 10km would be required for 97% call success. These figures are reduced significantly if there is an obstruction in the path. Adding a building on a 730m path gives a call success rate of 97%. However, if the outdoor micro cell has a power of 30dBm it is not possible to achieve a call success of 97% even with an obstructing building in the path unless the distance between the cells is unreasonably long.

We propose a maximum antenna height for outdoor installations of 10m as a means to reduce the occurrence of unobstructed interference paths. We also propose a maximum power level of 23dBm EIRP to prevent interference over a significant area.

Residential scenario

This analysis confirms that a GSM system based on a pico cell operating at the 0dBm power level can provide coverage in an example terraced house scenario.

A probabilistic analysis of interference between co-frequency indoor GSM pico cells located within a row of terraced houses indicates that a 97% probability of call success inside each house could be achieved with a separation of two houses.

A probabilistic analysis of interference between co-frequency indoor GSM pico cells located within houses in opposite terraces indicates that coordination will be required and that it will only be possible to assign frequencies from a total of 15 at random if the usage percentages are relatively low.

Use of low power CDMA

Under a technology neutral licence it is conceivable that both narrowband (e.g. low-power GSM) and wideband (e.g. low-power cdma2000 1x) systems could be deployed. As an example of the deployment of both wideband and narrowband systems, this analysis considers the impact of a low-power cdma2000 1x system on a low-power GSM system.

A probabilistic analysis of interference from an 23dBm indoor cdma2000 1x pico cell system into a co-frequency indoor GSM pico cell system indicates that achieving a 97% probability of call success inside the office would require a 250m separation distance between the buildings for a 50m radius serving cell if there were no obstructions between them. We conclude that coordination may be necessary.

Section 2

Introduction

The Spectrum Framework Review: Implementation Plan identified opportunities for making the spectrum bands 1781.7 – 1785 MHz paired with 1876.7 – 1880 MHz available for a range of innovative services based on low-power concurrent use. It defines "low-power" as being restricted to 23dBm (200mW) equivalent isotropic radiated power (EIRP) and proposes granting a limited number of UK low-power licences.

This study considers the impact of the 23dBm limit on the deployment of low-power systems. Capacity and coverage for office, campus and residential scenarios are considered alongside the need for coordination due to proximity of users sharing the same set of frequencies.

Methodology

The coverage and capacity requirements for an example multi-storey office building are calculated and converted to radio frequency requirements. This provides a check on whether the band has sufficient capacity for an office-based network. If there is spare capacity it provides an indication of how much scope there is for licensees to agree local band segmentation arrangements.

Next, the interference between neighbouring office pico cell systems is calculated. A probabilistic model of neighbouring office buildings using indoor low-power pico cells provides an indication of the likely coordination requirements. The pico cell power is set at 23dBm and omni directional antennas without gain are used in the model. The two pico cells are set to a single frequency and call success rates are calculated for a range of distances between buildings. The probabilistic model indicates the requirement for coordination and the likelihood of successful coordination between neighbours deploying low-power indoor systems.

An outdoor "campus" scenario is then modelled to establish the effects of different power levels. Outdoor micro cell coverage of nearby buildings is calculated and the interference impact of the micro cell on a co-frequency office pico cell system is determined, first using line of sight, then an obstructed path.

Two residential scenarios are modelled: the first examines the frequency re-use within a row of terraced houses; the second models the external interference effects between houses across a street. For these studies, a pico cell power of 0dBm was used.

A number of different generic scenarios were modelled to assess the potential impact of the transmitted power for a given quality of service level (97% call success rate) and the likelihood of the need to coordinate between near-by systems. A system designer may in practice do more precise modelling taking into account of the specific layout, building materials and the furniture inside the particular office block requiring the service.

Quality assurance

On completion of the study a peer review within Ofcom was used to verify the methodology and conclusions of the work and provide an internal quality assurance check.

Section 3

Coverage and capacity analysis

This analysis provides two functions. It confirms that a system operating at the 23dBm power level can provide coverage in an example multi-storey office scenario. It also calculates the capacity requirements and determines the amount of radio spectrum that a pico cell system would use to satisfy both the capacity and coverage needs.

System characteristics

Calculations were based on GSM pico cell deployments in office buildings. The pico cell base station characteristics used in the calculations were

Operating frequency: 1880 MHz
Power: 23dBm
Antenna gain: 0dBi
Cell radius: 50m

The building characteristics were

Building width: 50m
Building length: 120m
Population: 300 people per floor
Blocking probability: 2%

The peak traffic assumptions were for 20% of people to be involved in active calls of 5 minutes duration during the busy hour.

Methodology

The calculations were broken down into four elements:

1. Calculate the number of cells required to ensure adequate coverage based on the physical dimensions of the building.
2. Calculate the number of cells required to provide adequate traffic carrying capacity based on the number of occupants per floor.
3. Calculate the minimum radio frequency re-use distance between floors.
4. Confirm that the number of radio carriers allowed for traffic carrying capability will also meet the vertical re-use distance criteria.

A detailed description of the calculations is contained in Annex A.

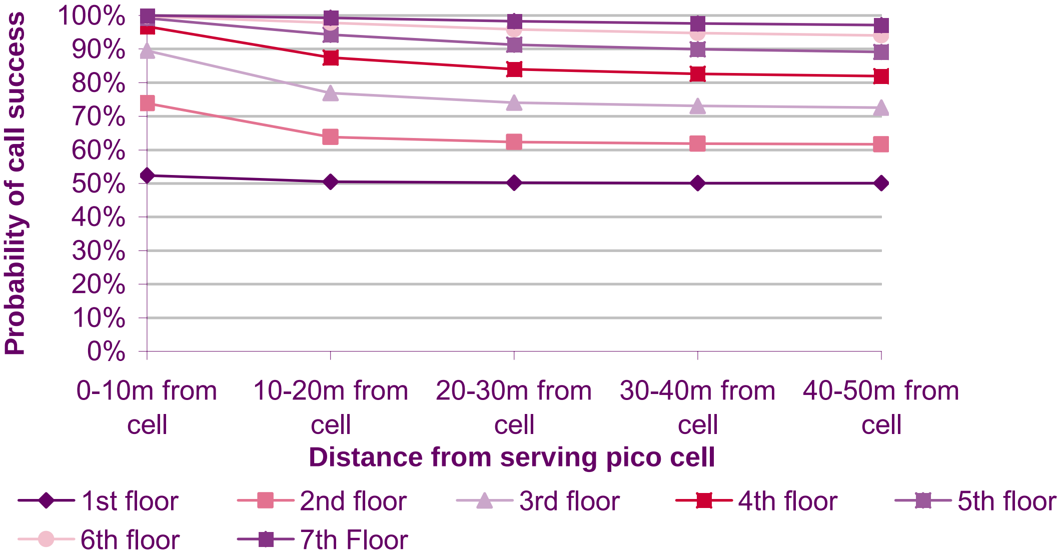
Results

Coverage predictions based on in-building propagation from Recommendation ITU-R P.1238-3 give a cell coverage radius of 50.6m. Two pico cells would provide floor coverage in the example office building used in this scenario.

Pico cell capacity is calculated to be 2.9 erlangs for one radio channel. For the building population modelled, the peak traffic requirement is 2.5 erlangs per cell, so the two pico cells would also meet the traffic requirements of the floor.

Results for frequency re-use were expressed in terms of the probability of successfully making a call on a particular floor if the ground floor radio frequencies were re-used by pico cells on that floor. These are shown graphically in Figure 1.

Figure 1. Probability of call success



On the basis that 94% - 99% probability of call success across the cell is acceptable, the radio frequencies can be re-used every six floors. The call success probabilities for the one floor, two floor, three floor, fourth floor and five floor re-use patterns are unlikely to be acceptable in the office environment. To maintain a minimum 97% call success probability across every cell would require a seven-floor re-use pattern.

Based on two pico cells per floor and a six-floor re-use, twelve radio channels would be required for coverage in the building. This is 80% of the available 15 carriers in the 1876.9 – 1880 MHz band (assuming that 1876.7 – 1876.9 MHz is kept as a guard channel to avoid interference between low-power GSM and wide area GSM). Under the seven-floor re-use arrangement, 14 of the 15 radio channels would be needed for the office.

It should be noted that the attenuation figures used in the calculations were taken from recommendation ITU-R P.1238-3. This recommendation stipulates an attenuation figure of 15dB for the first floor with correction factors added for multiple floors. A published work by ERA technology[*] suggests that these figures could be improved upon with more recent building construction methods. Attenuation figures of between 15 – 24dB per floor are quoted.

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[*] “Application of FSS structures to selectively control the propagation of signals into and out of buildings “ ERA report 2004-0072, Annex 2, page 13 figure 4.

Section 4

Office scenario: adjacent building interference

The aim of these calculations is to determine the necessary separation distance to avoid interference between low power GSM systems using the same radio channels in adjacent buildings.

System characteristics

Calculations were based on GSM pico cell deployments in office buildings. The pico cell base station characteristics used in the calculations were

Operating frequency: 1880 MHz
Power: 23dBm
Antenna gain: 0dBi
Cell service radius: 40m and 50m

The building width was set at 50m.

Methodology

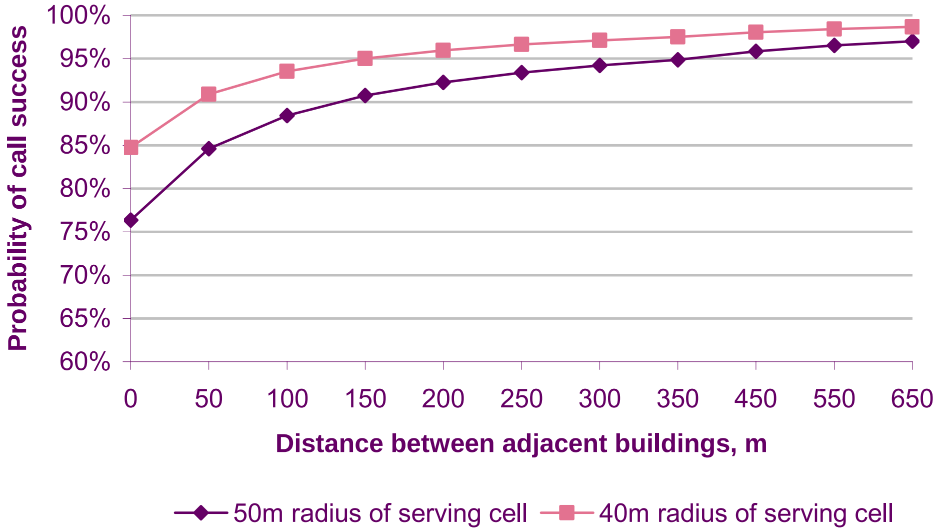
The main challenge for the probabilistic analysis is the variability of the received signal around the inside of the building and between buildings. A signal is assumed to suffer interference when the ratio of wanted signal to interfering signal is less than the minimum carrier-to-interference (C/I) ratio specified for the system. Both of these signals suffer variability and normally Monte Carlo modelling is used to overcome the problems created by the twin sources of variability. Fortunately, if both sources of variability are assumed to be Gaussian, it is possible to take the standard deviations from both the wanted and interfering path and to apply this to obtain the margin above minimum C/I and the probability of call success. The distributions would not be truly Gaussian but they are likely to be close enough to Gaussian for the method to be feasible.

A detailed description of the calculations is contained in Annex B.

Results

Results for the probabilistic study were provided in terms of call success probability for a range of distances between buildings. Figure 2 below shows this graphically.

Figure 2. Probability of call success for 23dBm base stations in adjacent office buildings



For adjacent in-building systems where each pico cell serves a 50m radius, 97% probability of call success inside each office could be achieved with 550m separation between buildings if there were no obstructions between them. For a building separation of 150m a 91% probability of call success is achieved.

We therefore conclude that coordination is necessary.

Use of higher base station power

The use of higher powers is not considered a realistic scenario for internal office deployment as the powers are out of the pico cell range as defined in the GSM specifications. This study depends on symmetric power levels for the above conclusions. If higher base station powers could be used, system operators would have an incentive to use the highest power possible to overcome interference from neighbouring systems. Use of higher powers by both sides would not change the carrier-to-interference ratio, so the coverage would not be improved. This leads us to conclude that it is in the interests of licensees to keep the maximum power limit to the lowest level possible that would permit coverage over the indoor area.

We therefore recommend a maximum power limit of 23dBm EIRP since this has been shown in Section 3 to meet the in-building coverage requirement.

Section 5

Campus scenario: coverage and interference

This analysis follows on from the work in Section 4 and considers the case where low-power GSM is used to provide coverage in a campus environment. Examples could include a university or a business park. Some outdoor deployment is envisaged along with the use of higher powers to cover external areas between buildings. Some buildings are served by external base stations that are visible through the windows.

The campus scenario permits consideration of powers above 23dBm. The aim is to determine the optimum power level for low-power concurrent licences.

System characteristics

Calculations are based on a mix of GSM pico cell deployments in office buildings and outdoor GSM micro cell deployment. The pico cell base station characteristics used in the calculations are

Operating frequency: 1880 MHz
Power: 23dBm
Antenna gain: 0dBi
Cell radius: 50m

The micro cell base station characteristics are

Operating frequency: 1880 MHz
Power: 23dBm to 30dBm EIRP

Methodology

A building served by an outdoor micro cell is modelled. Coverage inside the building is calculated in order to indicate whether this is a viable deployment scenario.

An in-building pico cell office system identical to that in Section 4 is modelled next. An outdoor micro cell system is introduced on the same radio channel and the interference into the pico cell system is calculated for micro cell powers of 23dBm, 26dBm and 30dBm. Additional buildings are then placed in the path between the outdoor micro cell and the office and the impact on separation requirement is determined. The study assesses the impact of power output on separation requirements.

Results

For the case where an external micro cell is used to provide coverage inside a building, the maximum distance of the micro cell from the building for a range of powers is shown in Table 1.

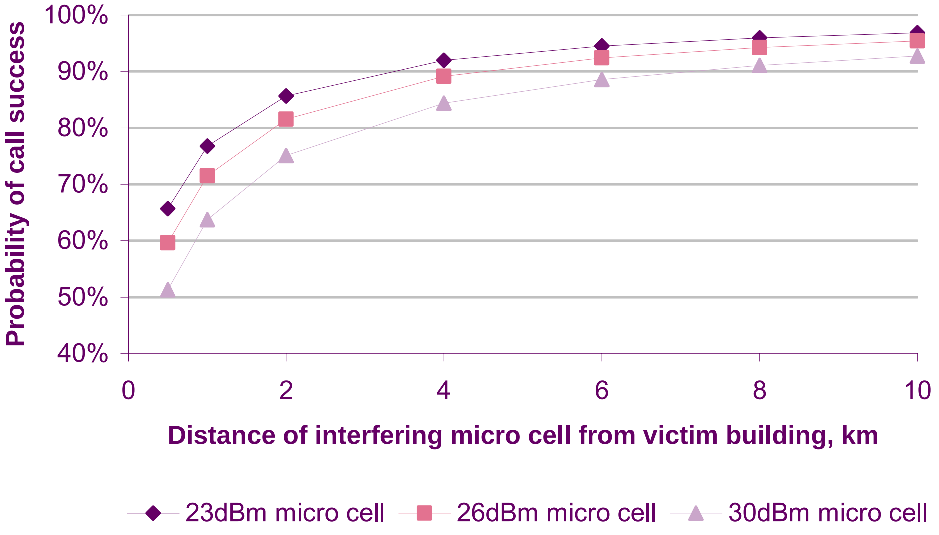
Table 1. Maximum distance between micro cell and building

	Penetration distance in-building, m	Maximum distance between micro cell and outside of building (90% call success probability), m	Maximum distance between micro cell and outside of building (97% call success probability), m
23dBm micro cell	30	255	137
	40	112	49
	50	35	Not possible
26dBm micro cell	30	372	206
	40	174	86
	50	69	20
30dBm micro cell	30	607	344
	40	300	160
	50	139	61

We conclude that it is possible to serve users up to 40m within a building using an external base station with a power limit of 23dBm. However, to penetrate to users 50 meters within a building would require a higher power (30dBm would be needed to give a reasonable separation between the base station and building).

For the case of an in-building pico cell network suffering interference from an external micro cell, results were obtained in terms of call success probability for varying separations between the building and the micro cell for an unobstructed path. These are shown in Figure 3.

Figure 3. Probability of call success for unobstructed path from interfering micro cell



At 3km a 23dBm micro cell reduces the call success probability on the pico cell system below 90% while a separation of 10km would be required for 97% call success. These figures indicate the potential for external micro cells to cause interference over a significant area.

When a building of greater height than the interfering micro cell antenna is added between the micro cell and the office pico cell system the figures improve, as shown in Figure 4.

Figure 4. Probability of call success with a single intermediate building between the micro cell and victim receiver

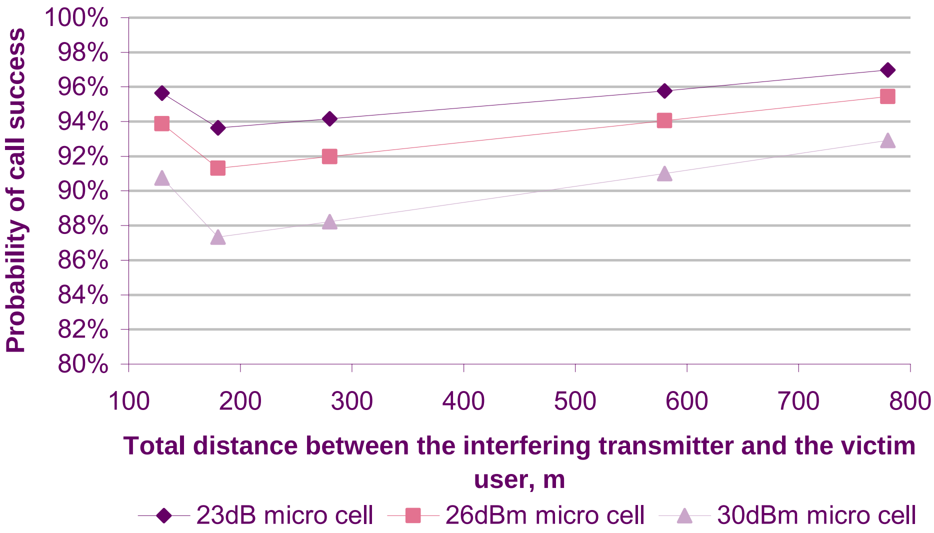
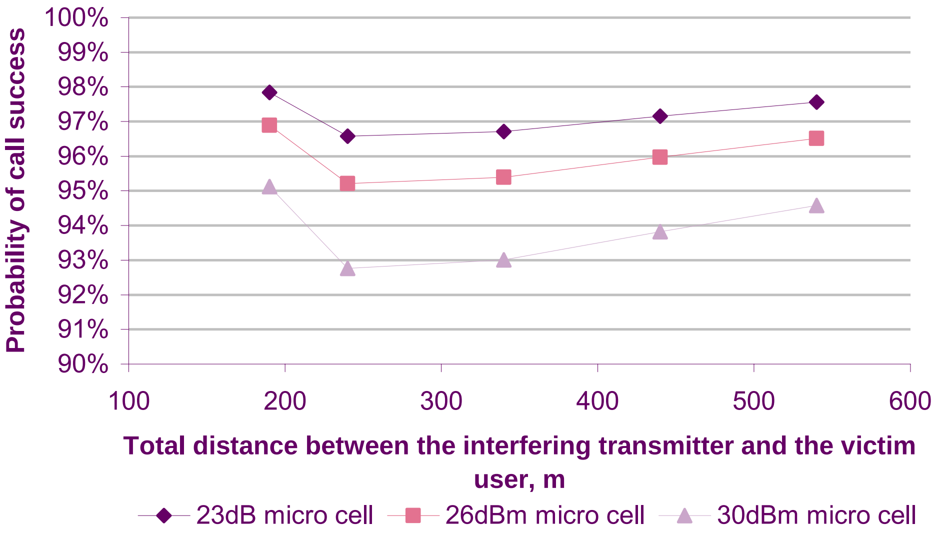


Figure 5. Probability of call success with two intermediate buildings between the micro cell and victim receiver



These results are a substantial improvement over the case of the unobstructed path. With a single intermediate building, the 23dBm micro cell interferer did not reduce call success below 93%. With two intermediate buildings, the 23dBm micro cell interferer did not reduce call success below 96.6%. However, if the outdoor micro cell has a power of 30dBm, with a single intermediate building, it is not possible to achieve a call success probability above 93% over the distance modelled and with two intermediate buildings the call success probability ranged between 92 - 95% over the distance modelled.

We propose a maximum antenna height of 10m above ground level for outdoor antennas in order to reduce the probability of unobstructed interference paths. This restriction need not apply to indoor installations due to the additional building losses indicated in Annex B. We also propose a maximum power level of 23dBm EIRP for outdoor installations to prevent interference over a significant area.

Section 6

Residential scenario

This section is intended to model the use of pico cells by householders to provide cordless telephony within the home on a GSM handset.

Scenarios modelled

Two deployment scenarios are modelled in this section. The first is a modelling of the frequency re-use factor within a row of terraced houses, when a 0dBm GSM pico cell is installed in each house. The second scenario models the potential for interference between houses across a street.

System characteristics

Operating frequency: 1880 MHz
Power: 0dBm EIRP
Antenna gain: 0dBi

The required pico cell power was calculated on the basis of the longest path distance within a house. The loss calculations include a fade margin calculated to ensure 90% probability of call success at the cell edge, which yields a 97% call success rate over the cell area.

Methodology for Scenario 1: frequency re-use in a row of terraced houses.

For this particular scenario, both the interferer house and the victim house were partitioned into five areas. It is assumed that there is an equal probability that a transmitter or user would be positioned within any of these areas. This gives a total of twenty five possible distances between the wanted signal path and the unwanted (interfering) signal path. The wanted and unwanted signal strengths were then calculated for all twenty five possible distances. The results were then used to calculate the margin above C/I for each value. As before, the normalised variable z was calculated from the root sum of squares of the standard deviation for fading, and the results average to find the probability of call success.

The method was used to calculate the probability of call success for the first house from the interferer, the second house from the interferer, third house, etc until a successful call probability value of above 97% was reached.

Results

The results of the probability calculations are in Table 2.

Table 2. Probability of call success in adjacent houses

Distance from interferer	Average probability of call success
First house	33%
Second house	80%
Third house	98.6%

The above results indicate that a frequency can be re-used every third house.

Methodology for Scenario 2: potential for interference between houses across a street

The interference signal strengths were calculated from the path loss of the rays propagating across the street to the victim house and contained within an arc -70° to +70°. The loss was calculated from a range of positions in the victim house over this arc.

The path loss for each angle is determined by selecting the minimum loss for a particular transmission path and adding the factor for the losses within the building.

The transmission methods considered for each path are:

- penetration through the structure
- reflection from the internal surfaces and out through the windows
- diffraction around the edges of the window

For each test point to an opposite house, the total loss was calculated by combining the minimum loss to exit the building, the free space path loss and marginal losses resulting from the clutter within the victim building. It should be noted that where there is internal reflection this has had to be included on an as-occurs basis.

Results

The results of the probability calculations are in Table 3.

Table 3. Probability of call success in buildings across the street

Angle arc from interferer	Floor of building	Mean probability of call success in building of parallel row
0°	ground	79.9%
0°	first	66.1%
30°	first	79.0%
50°	first	89.3%

The critical case is the first floor. A 30° span at the width of the street is a 12m span or 3 houses. 50° each side of the house subtends 28.6m which represents approximately six houses. This represents six frequencies on one side of the road, six on the other side and six behind the row of houses, i.e. 3 channels more than the maximum 15 channels available. We therefore conclude that coordination will be required and that it will only be possible to assign frequencies from a total of 15 at random if the usage percentages are relatively low.

Section 7

Office scenario: adjacent building using low-power CDMA

Under a technology neutral licence it is conceivable that both narrowband (e.g. low-power GSM) and wideband (e.g. low-power cdma2000 1x) systems could be deployed. As an example of the deployment of both wideband and narrowband systems, this analysis considers the impact of a low-power cdma2000 1x system on a low-power GSM system. The aim of these calculations is to determine the necessary separation distance to protect a low power GSM system in adjacent building from a low power cdma2000 1x system using the same centre frequency.

System characteristics

Calculations were based on cdma2000 1x and GSM pico cell deployments in office buildings. The pico cell base station characteristics used in the calculations were

System: GSM
Centre frequency: 1880 MHz
Bandwidth: 0.2MHz
Power: 23dBm
Antenna gain: 0dBi
Cell service radius: 40m and 50m

System: cdma2000 1x
Centre frequency: 1880 MHz
Bandwidth: 1.25MHz
Power: 23dBm
Antenna gain: 0dBi
Cell service radius: 40m and 50m

The building width was set at 50m.

Methodology

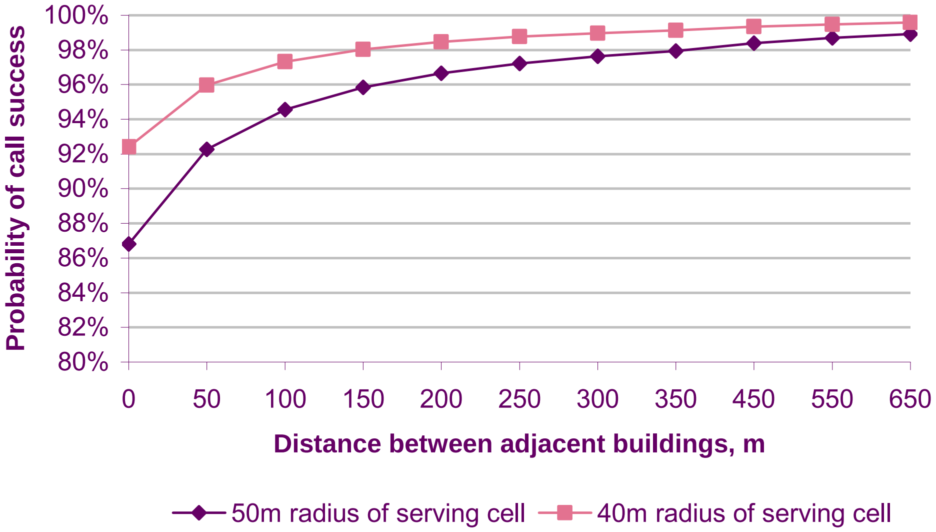
The main challenge for the probabilistic analysis is the variability of the received signal around the inside of the building and between buildings. A signal is assumed to suffer interference when the ratio of wanted signal to interfering signal is less than the minimum carrier-to-interference (C/I) ratio specified for the system. If both sources of variability can be assumed to be Gaussian, it is possible to take the standard deviations from both the wanted and interfering path and to apply this to obtain the margin above minimum C/I and the probability of call success. It is unlikely that the distributions would be truly Gaussian but they are likely to be close enough to Gaussian for the method to provide representative results.

A detailed description of the calculations is contained in Annex E.

Results

Results for the probabilistic study are provided in terms of call success probability for a range of distances between buildings. Figure 6 below shows this graphically.

Figure 6. Probability of call success for a low power GSM base station in adjacent office building to a low power cdma2000 1x system



Conclusion

Achieving a 97% probability of call success on the GSM system would require a 250m separation distance between buildings for a 50m radius serving cell if there were no obstructions between them.

We conclude that coordination will be required.

Section 8

Conclusions and recommendations

On the basis of the studies in this report, we recommend the following:

1. Power limit of 23dBm EIRP

This is sufficient power to provide coverage using an in building pico cell network. It also provides the ability to use an external base station to provide service inside nearby buildings (up to 40m).

2. Coordination is necessary

Neighbouring office pico cell systems will need coordination, no matter what technology is deployed.

3. Maximum height for outdoor antennas should be 10m above ground level

Unobstructed paths can cause interference to nearby in-building pico cell systems over a wide area. Setting a maximum antenna height of 10m for outdoor antennas will increase the probability of buildings or other obstructions appearing in the path.

Annex A

Coverage and capacity calculations

This annex describes the calculations to determine the radio spectrum requirements to fulfil the coverage and capacity requirements for an example multi-story office building.

The calculations were broken down into three elements:

1. Calculate the number of cells required to ensure adequate coverage based on the physical dimensions of the building.
2. Calculate the number of cells required to provide adequate traffic carrying capacity based on the number of occupants per floor.
3. Calculate the minimum radio frequency re-use distance between floors. This will confirm that the number of radio carriers required for traffic carrying capability will also meet the floor coverage requirements.

Calculating wanted signal from serving pico cell in own building

Initially a single pico cell with a serving radius of 50m is considered. For the purposes of this calculation the coverage is broken into concentric rings at 10m, 20m, 30m, 40m and 50m from the transmitter. The user is placed at the mid-point between each ring and the signal level is calculated. This is illustrated in Figure A.1, where the user is in the 10-20m ring and a distance of 15m is used in the propagation calculations.

Figure A.1. Distance of user from wanted transmitter

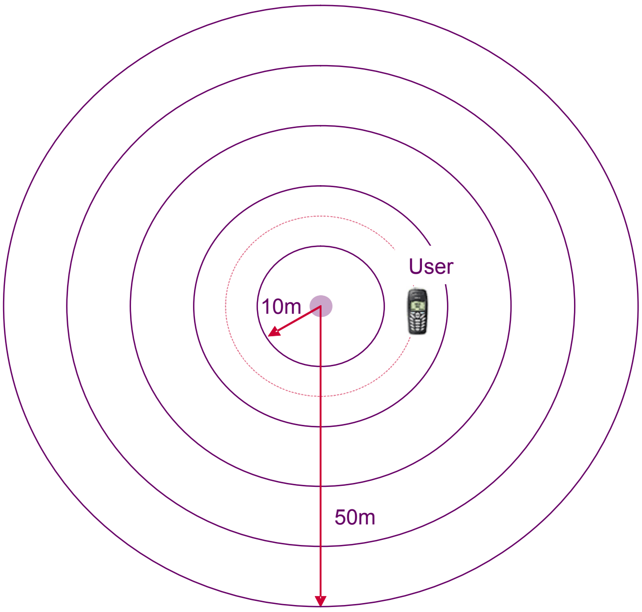


Table A.1 gives the calculated interference levels that can be tolerated based on a 23dBm pico cell base station.

Table A.1: Received signal levels from a 23dBm pico cell base station

Distance from pico cell, m	Path loss in building, dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
0-10	71.5	-37.5	9	-46.5
10-20	84.5	-55.8	9	-64.8
20-30	93.8	-66.4	9	-75.4
30-40	101.5	-74.8	9	-83.8
40-50	108.5	-82.1	9	-91.1

Coverage calculations

For the example scenario the office building dimensions are:

Building width: 50m
Building length: 120m
Floor area: 6,000m^2

The system parameters are

Operating frequency: 1880 MHz
Power: 23dBm EIRP
Mobile station receiver sensitivity: -102dBm (source: GSM 05.05)
Body and matching loss: 6dB (source: S.Saunders, *Antennas and propagation for wireless communication systems*, Wiley 1999)
Shadow fading: 10dB (source: Recommendation ITU-R P.1238-3)

These figures give a maximum allowable path loss of 109dB

The propagation model was taken from Recommendation ITU-R P.1238-3, *Propagation data and prediction methods for the planning of indoor Radiocommunications systems and radio local area networks in the frequency range 900 MHz to 100 GHz*.

Using the general in building propagation loss formula:

$$L = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28$$

Where

L	path loss	109dB
f	frequency	1880 MHz
d	distance from transmitter	

We can calculate the cell coverage radius at 50.6m.

We therefore conclude that two pico cells will be required to cover the 120m floor length.

Capacity calculations

The required traffic capacity was estimated using the following criteria:

N = Number of people per cell area = 150

P = Proportion engaged on a call during the busy hour = 0.2
D = Duration of the call, minutes = 5

Calculated traffic capacity is given by the following formula

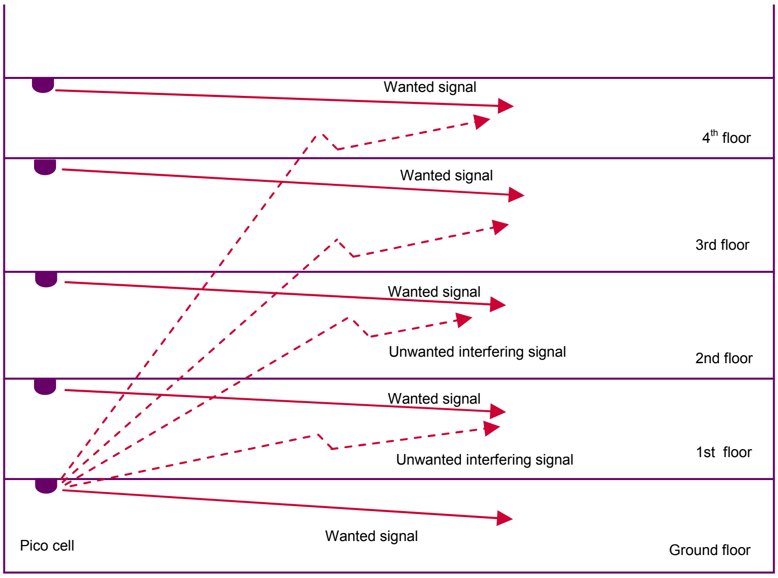
$$\text{Traffic capacity} = \frac{NPD}{60} = 2.5 \text{ erlangs}$$

Based upon the Erlang B formula, traffic capacity for one radio channel comprising 8 user time slots and a 2% blocking probability will be 2.9 erlangs. Assuming an even deployment of people across the office floor, the two pico cells per floor required for coverage will accommodate the expected traffic demand.

Interference between floors

In order to determine the required number of radio carriers for the total building needs, the vertical re-use pattern must be checked. Figure A.2 shows the interference paths within the building from a pico cell on the ground floor.

Figure A.2. Interference paths from ground floor



For each floor the path length from the interfering pico cell was calculated at 10m intervals. This then allows a path loss to be calculated. Table A.2 shows the path lengths for the interfering signal based on height of 3m per floor. The pico cells are assumed to be mounted 2.5m above floor level and the handset 1.5m above floor level.

Table A.2. Path length for interfering signal

Interference path	Length of interference path, m 0-10m along floor	10-20m along floor	20-30m along floor	30-40m along floor	40-50m along floor
Ground to 1st floor	5.4	15.1	25.1	35.1	45.0
Ground to 2nd floor	7.1	15.8	25.5	35.4	45.3
Ground to 3rd floor	9.4	17.0	26.2	35.9	45.7
Ground to 4th floor	12.1	18.6	27.3	36.7	46.3
Ground to 5th floor	14.9	20.5	28.7	37.7	47.1
Ground to 6th floor	17.7	22.7	30.2	38.9	48.1
Ground to 7th floor	20.6	25.0	32.0	40.3	49.2

Table A.3 now shows the interfering signal from a 23dBm pico cell located on the ground floor subject to the propagation loss calculated using

$$L = 20 \log_{10} f + 30 \log_{10} d + 0.4d + L_{floor} - 28$$

where L_{floor} is floor penetration loss defined in Recommendation ITU-R P.1238-3 for an office building of n floors by the formula

$$L_{floor} = 15 + 4 (n - 1)$$

The figures in Table A.3 also include a fast fading margin of 6dB.

Table A.3. Interference signal power from the ground floor level.

	Interference signal power, dBm 0-10m along floor	10-20m along floor	20-30m along floor	30-40m along floor	40-50m along floor
1st floor	-47.6	-64.9	-75.5	-83.8	-91.1
2nd floor	-55.8	-69.8	-79.9	-88.1	-95.3
3rd floor	-64.5	-75.2	-84.6	-92.5	-99.6
4th floor	-72.8	-81.0	-89.5	-97.1	-104.0
5th floor	-80.6	-87.1	-94.7	-101.9	-108.5
6th floor	-88.0	-93.2	-100.0	-106.7	-113.2
7th floor	-95.2	-99.4	-105.5	-111.8	-118.0

We now derive figures for the margin above the minimum C/I required to make a call by subtracting the interference signal power in Table A.3 from the maximum permitted interference levels in Table A.1. The values are tabulated below in Table A.4.

Table A.4. Margin above minimum C/I

	Margin above minimum C/I, dB				
	0-10m along floor	10-20m along floor	20-30m along floor	30-40m along floor	40-50m along floor
1st floor	0.8	0.1	0.1	0.0	0.0
2nd floor	9.0	5.0	4.4	4.3	4.2
3rd floor	17.8	10.4	9.1	8.7	8.5
4th floor	26.0	16.2	14.1	13.3	12.9
5th floor	33.8	22.2	19.2	18.0	17.4
6th floor	41.3	28.4	24.6	22.9	22.1
7th floor	48.4	34.6	30.0	28.0	26.9

In order to find the probabilities of signal interference, it was necessary to find the total standard deviation for the wanted and unwanted signals, using the root sum of square method. The 10dB standard deviation values for signal fading were taken from Recommendation ITU-R P 1238.

The total standard deviation is therefore:

$$\sqrt{10^2 + 10^2} = 14.14$$

The standardised normal variable (Z) is the difference between the mean interfering signal and signal to be protected expressed as a number of standard deviations. The Z value was calculated by the division of the total standard deviation value of 14.14 into the values obtained in Table A.4.

Table A.5 below shows the intermediate step of calculated Z values.

Table A.5 Normalised Z values

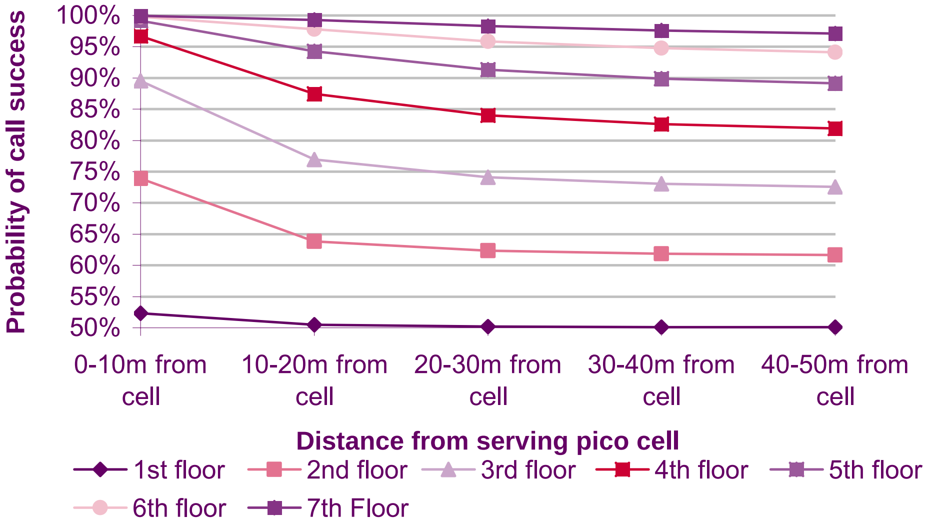
	Normalised Z value				
	0-10m along floor	10-20 m along floor	20-30m along floor	30-40m along floor	40-50m along floor
1st floor	0.06	0.01	0.00	0.00	0.00
2nd floor	0.64	0.35	0.31	0.30	0.30
3rd floor	1.26	0.73	0.64	0.61	0.60
4th floor	1.84	1.15	0.99	0.94	0.91
5th floor	2.39	1.57	1.36	1.28	1.23
6th floor	2.92	2.01	1.74	1.62	1.56
7th floor	3.42	2.45	2.12	1.98	1.90

The result was referenced to Gaussian tables to determine the probability that the desired signal to noise ratio is maintained and is expressed as a call success probability. The figures are given per floor, per 10m incremental distance from the serving cell. They are shown below in table A.6 and graphically in Figure A.3.

Table A.6. Probability of call success

	Probability of call success				
	0-10m from cell	**10-20m from cell**	**20-30m from cell**	**30-40m from cell**	**40-50m from cell**
1st floor	52.3%	50.4%	50.2%	50.1%	50.1%
2nd floor	73.9%	63.7%	62.3%	61.8%	61.6%
3rd floor	89.5%	76.9%	74.0%	73.0%	72.6%
4th floor	96.7%	87.4%	84.0%	82.6%	81.9%
5th floor	99.2%	94.2%	91.3%	89.9%	89.1%
6th floor	99.8%	97.8%	95.9%	94.8%	94.1%
7th floor	100.0%	99.3%	98.3%	97.6%	97.1%

Figure A.3. Probability of call success per floor.



On the basis that 94% - 99% probability of call success across the cell is acceptable, the radio frequencies can be re-used every six floors. The call success probabilities for the one floor, two floor, three floor, fourth floor and five floor re-use patterns are unlikely to be acceptable in the office environment. To maintain a minimum 97% call success probability across every cell would require a seven-floor re-use pattern.

Based on two pico cells per floor and a six floor re-use, twelve radio channels would be required for coverage in the building. This is 80% of the available 15 carriers in the 1876.9 – 1880 MHz band (assuming that 1876.7 – 1876.9 MHz is kept as a guard channel to avoid interference between low-power GSM and wide area GSM). Under the seven-floor re-use arrangement, 14 of the 15 radio channels would be needed for the office.

It should be noted that the attenuation figures used in the calculations were taken from recommendation ITU-R P.1238. This recommendation stipulates an attenuation figure of 15dB for the first floor with correction factors added for multiple floors. A published work by ERA technology[†] suggests that that improvement can be expected

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[†] "Application of FSS structures to selectively control the propagation of signals into and out of buildings " ERA report 2004-0072, , Annex 2, page 13 figure 4.

due to the higher attenuation losses with more recent building construction methods. Attenuation figures of between 15 – 24dB per floor are quoted.

Annex B

Office scenario calculations

These calculations assess the feasibility of using internal pico cells in adjacent office buildings and whether coordination might be required if both offices use the same channel. The effect of building separation is modelled, to determine the potential success of any coordination.

Modelling the necessary separation distance to avoid interference between low power GSM systems in adjacent buildings

The main challenge for this problem is the variability of the received signal around the inside of the building and between buildings. A signal is assumed to suffer interference when the ratio of wanted signal to interfering signal is less than the minimum carrier-to-interference (C/I) ratio specified for the system. Both of these signals suffer variability and normally Monte Carlo modelling is used to overcome the problems created by the twin sources of variability. Fortunately, if both sources of variability are assumed to be Gaussian, it is possible to take the standard deviations from both the wanted and interfering path and to apply this to obtain the margin above minimum C/I and the probability of call success. The distributions would not be truly Gaussian but they are likely to be close enough to Gaussian for the method to be feasible.

Propagation model

Within the building the field strength will be reduced by diffraction, where the first Fresnel zone is obstructed (due to building layout and office furniture). Recommendation ITU-R P.1238-3 provides the following equation to calculate the propagation losses within buildings:

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_{floor}(n) - 28 \qquad \text{dB}$$

where:

L_{total} : total propagation loss
N : distance power loss coefficient
f : frequency (MHz)
d : separation distance (m) between the base station and portable terminal (where $d \geq 1$m)
L_{floor} : floor penetration loss factor (dB)
n : number of floors between base station and portable terminal ($n \geq 1$).

Recommendation ITU-R P.1238-3 indicates that the typical value for N within an office building is 30 (losses within a building due to floor penetration are not considered).

Additional losses of wall partitions are to be included. This study assumed a loss of 4dB per wall that is every 10m. This loss value is taken from COST 231.

The in-building propagation loss equation becomes:

$$L = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 \qquad \text{dB}$$

where

d : separation distance (m) between the base station and portable terminal (where d ≥ 1m)

Calculating wanted signal from serving pico cell in own building

A single pico cell with a serving radius of 50m is considered. For the purposes of this calculation the coverage is broken into concentric rings at 10m, 20m, 30m, 40m or 50m from the transmitter. The user is placed at the mid-point between each ring and the signal level is calculated. This is illustrated in Figure B.1 where the user in the 10 – 20m ring a distance of 15m is used in the propagation calculations.

Figure B.1. Distance of user from wanted transmitter

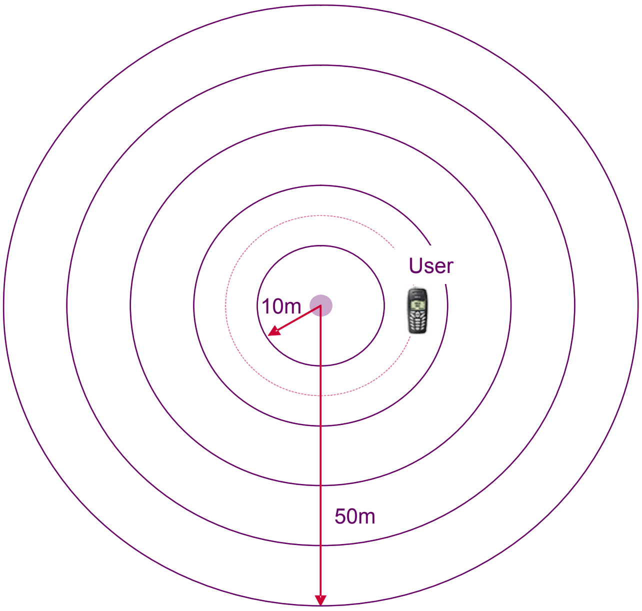


Table B.1 gives the calculated interference levels that can be tolerated based on a 23dBm pico cell base station based on the above propagation loss equation.

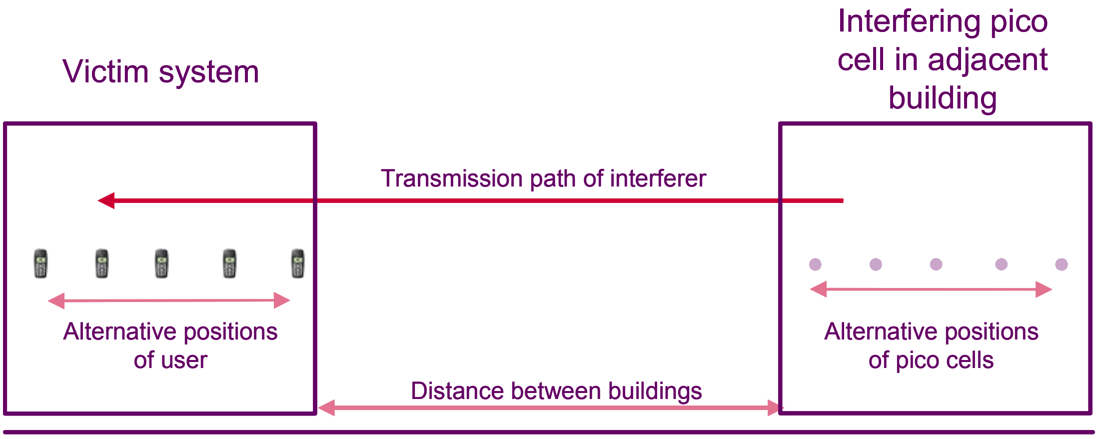
Table B.1: Received signal levels from a 23dBm pico cell base station

Distance from pico cell, m	Path loss in building, dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
0 - 10	71.5	-37.5	9	-46.5
10 - 20	84.5	-55.8	9	-64.8
20 - 30	93.8	-66.4	9	-75.4
30 - 40	101.5	-74.8	9	-83.8
40 - 50	108.5	-82.1	9	-91.1

Interference from a pico cell in an adjacent building

To model the interference into the receiver we consider a pico cell in an adjacent building which has a serving radius of 50m. The interfering signal exits from an adjacent building through the window, crosses the intervening space, then enters through another window to reach the user's terminal. Figure B.2 illustrates the path of the interfering signal.

Figure B.2. Interfering signal path



The field strength within the victim building from the interferer cannot directly be calculated by the in-building equations because the interfering signal has already passed through a space (between the buildings) without in-building loss before entering the victim building. This problem can be addressed by calculating the path losses relative to free space path loss to find the path loss due only to the building conditions. These figures are added to the free space path loss for the total distance in order to obtain the combined loss for a range of separation distances.

The losses for each part of this path are:

$$L_{FreeSpace} = 20 \log_{10} f + 20 \log_{10} d - 28$$

$$L_{Inbuilding} = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 + 4$$

$$L_{BuildingOnly} = L_{Inbuilding} - L_{FreeSpace} = 10 \log_{10} d + 0.4d + 4$$

$L_{Inbuilding}$ has an additional loss of 4dB caused by the interfering signal exiting or entering each building via the windows.

The pico cell and user can be positioned anywhere within the building, varying the potential total length of the interfering path and the likely received interfering signal. Tables B.2 and B.3 show the in-building penetration loss for various positions of interferer and victim receiver. Table B.4 shows the potential combinations of total penetration losses in both buildings.

Figure B.3. Breakdown of the calculation of the transmission path of interferer

Table B.2: Penetration in adjacent building

Distance of transmitter from window in adjacent building, m	Penetration loss, dB ($L_{BuildingOnly}$)
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

Table B.3: Penetration in victim building

Distance of user from window in victim building, m	Penetration loss, dB ($L_{BuildingOnly}$)
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

Table B.4: Matrix of the potential total penetration losses of the interfering signal in the victim and adjacent building, dB (derived by calculating the possible combinations of total penetration loss from table B.2 and table B.3).

Distance of user from window in victim building, m	**Penetration loss, dB**				
	Distance of transmitter from window in adjacent building				
	0 - 10m	**10 - 20m**	**20 - 30m**	**30 - 40m**	**40 - 50m**
0 - 10	26.0	34.8	41.0	46.4	51.5
10 - 20	34.8	43.5	49.7	55.2	60.3
20 - 30	41.0	49.7	56.0	61.4	66.5
30 - 40	46.4	55.2	61.4	66.9	72.0
40 - 50	51.5	60.3	66.5	72.0	77.1

The mean penetration loss due to positional variation, $\overline{X}$ = 53.88dB

The sample standard deviation of data in a sample is calculated by:

$$\text{Standard deviation} = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}(X_i - \overline{X})^2}$$

The standard deviation calculated is 12.90dB. This represents the variation of penetration loss due to different placements of the interfering transmitter and the victim user terminal.

There are additional variations to consider due to shadowing, when modelling the variation in the received signals, these are assumed to be

- 10dB from the wanted transmitter to the user, from Recommendation ITU-R P.1238-3.
- 7.7dB from the interfering signal, from its mixed propagation path.

The total standard deviation for the entire path is

$$\sqrt{7.7^2 + 10^2 + 12.90^2} = 18.04$$

The mean interfering signal received by the user is calculated by the addition of free space path loss plus the mean in-building loss due to positional variations of the interfering transmitter and the victim user and a fast fading margin of 6dB.

Table B.5: Mean interfering signal level in victim building from 23dBm outdoor pico cell

Total distance between user and interfering cell, m	Free space path loss, dB	Mean in-building penetration loss, dB	Mean interfering signal received by user, dBm
50	71.5	53.88	-96.3
100	77.5	53.88	-102.4
150	81.0	53.88	-105.9
200	83.5	53.88	-108.4
250	85.4	53.88	-110.3
300	87.0	53.88	-111.9
350	88.4	53.88	-113.2
400	89.5	53.88	-114.4
500	91.5	53.88	-116.3
600	93.0	53.88	-117.9
700	94.4	53.88	-119.3

Calculating the likelihood of call success

It is possible to obtain the interference for the entire victim cell by slicing the cell into 10m rings and estimating the percentage interference for each of these rings using standard statistical methods.

Table B.6: Difference between signal to be protected and mean interfering signal

	Margin above minimum C/I, dB										
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user										
	50m	100m	150m	200m	250m	300m	350m	400m	500m	600m	700m
0 - 10	49.89	55.91	59.43	61.93	63.87	65.45	66.79	67.95	69.89	71.48	72.81
10 - 20	31.58	37.60	41.12	43.62	45.56	47.14	48.48	49.64	51.58	53.16	54.50
20 - 30	20.92	26.94	30.46	32.96	34.90	36.49	37.82	38.98	40.92	42.51	43.84
30 - 40	12.54	18.56	22.08	24.58	26.52	28.10	29.44	30.60	32.54	34.12	35.46
40 - 50	5.26	11.28	14.81	17.31	19.24	20.83	22.17	23.33	25.26	26.85	28.19

The standardised normal variable is the difference between the mean interfering signal and signal to be protected expressed as a number of standard deviations. The table below is an interim step, where the standardised normal variable, Z, has been found in order to calculate the probability of a successful call using a Gaussian distribution table, see table B.8.

Table B.7: Standardised normal variable, Z

Distance of user from own pico cell, m	Standardised normal variable										
	Distance of the interfering transmitter from the victim user										
	50m	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0 - 10	2.76	3.10	3.29	3.43	3.54	3.63	3.70	3.77	3.87	3.96	4.04
10 - 20	1.75	2.08	2.28	2.42	2.52	2.61	2.69	2.75	2.86	2.95	3.02
20 - 30	1.16	1.49	1.69	1.83	1.93	2.02	2.10	2.16	2.27	2.36	2.43
30 - 40	0.69	1.03	1.22	1.36	1.47	1.56	1.63	1.70	1.80	1.89	1.97
40 - 50	0.29	0.63	0.82	0.96	1.07	1.15	1.23	1.29	1.40	1.49	1.56

(standard deviation=18.04)

Table B.8 shows the probability of a successful call if the user is within the 10m, 20m, 30m, 40m or 50m ring from the wanted pico cell for various distances of the path length of the interferer.

Table B.8: Probability of call success

Distance of user from own pico cell, m	Probability of successful call										
	Distance of the interfering transmitter from the victim user										
	50m	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0 - 10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 - 20	0.96	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
20 - 30	0.88	0.93	0.95	0.97	0.97	0.98	0.98	0.98	0.99	0.99	0.99
30 - 40	0.76	0.85	0.89	0.91	0.93	0.94	0.95	0.96	0.96	0.97	0.98
40 - 50	0.61	0.73	0.79	0.83	0.86	0.88	0.89	0.90	0.92	0.93	0.94

Assuming an even distribution of users within the cell, the following figures (Table B.9) can be derived for users at particular distances from the cell.

Table B.9: Distribution of users within cell

Distance from pico cell, m	Area of ring, m^2	Proportion of users
0 - 10	314.2	0.04
10 - 20	942.5	0.12
20 - 30	1570.8	0.20
30 - 40	2199.1	0.28
40 - 50	2827.4	0.36

To calculate the total probability of the cell receiving interference, users are assumed to be evenly distributed in the cell.

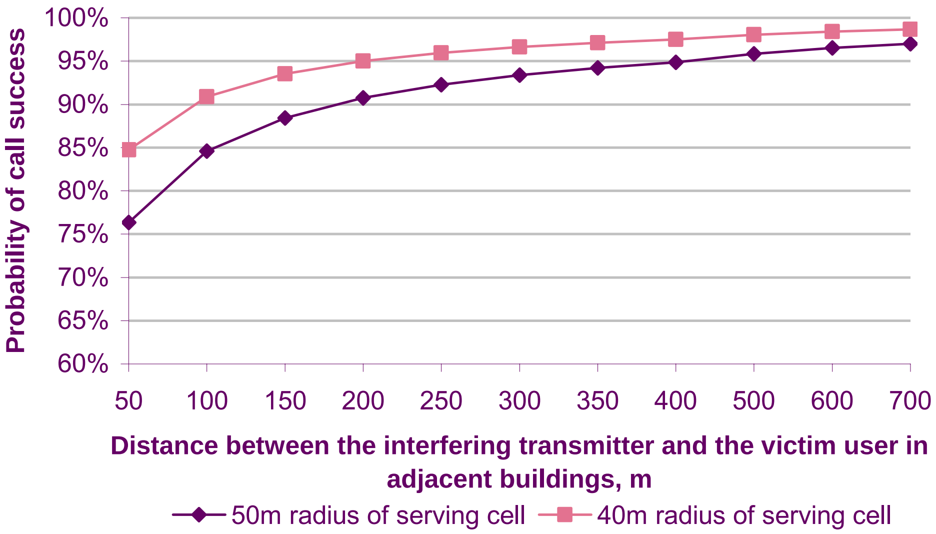
Table B.10 shows the total probability of a successful call and is derived by taking the probability of a successful call multiplying by the proportion of users. These values are added together to find the total probability of call success.

Table B.10: Total probability of call success for a 50m serving pico cell

	Proportion of successful calls										
Distance of user from own pico cell, m	**Distance of the interfering transmitter from the victim user**										
	50m	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0-10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
10-20	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
20-30	0.18	0.19	0.19	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20
30-40	0.21	0.24	0.25	0.26	0.26	0.26	0.27	0.27	0.27	0.27	0.27
40-50	0.22	0.26	0.29	0.30	0.31	0.32	0.32	0.32	0.33	0.34	0.34
Total probability	0.76	0.85	0.88	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.97

Figure B.4 shows the call success probability for a 50m cell from Table B.10. For comparison the probability for a 40m cell serving radius was calculated and is also shown.

Figure B.4. Probability of call success for 23dBm base stations in offices



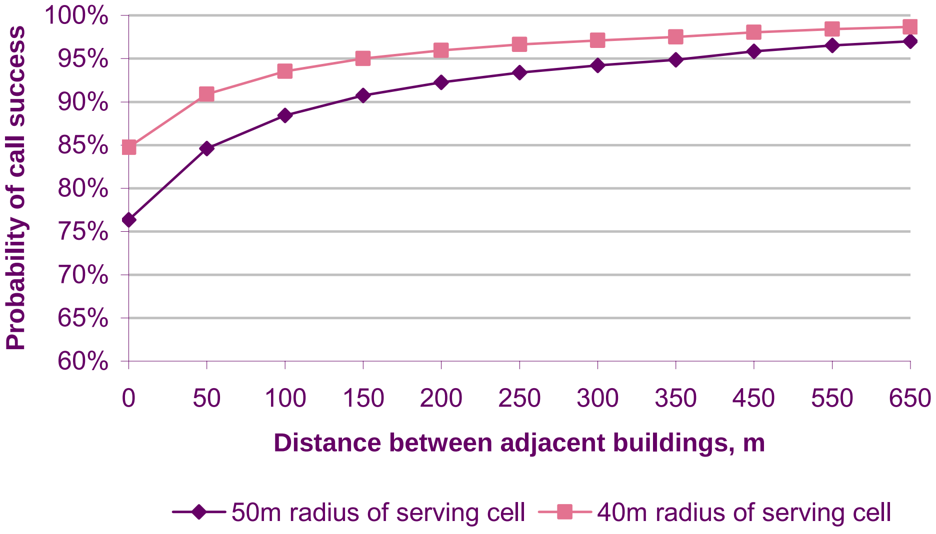
For a serving cell of radius 50m, to achieve a 90% probability of call success the model suggests that there is a distance between the interfering transmitter and the victim user of approximately 200m. For a serving cell of radius 40m, to achieve a 90% probability of call success the model suggests that there is a distance between the interfering transmitter and the victim user of approximately 100m.

To achieve a 97% probability of a successful call, the separation distance between the user and the interfering transmitter has to be 600m for a 50m radius serving cell and 250m for a 40m serving cell.

With adjacent office buildings of floor dimensions of 50m x 120m, it is possible to achieve some of the separation by positioning the cells using the same channel at opposite ends of the length of the building or on different floors to assure the 97% call success. This requires coordination of the planning stage when designing the positions of pico cells to achieve a 97% call success rate.

These probabilistic studies reveal that coordination is likely to be required.

Figure B.5: Probability of call success for 23dBm base stations in offices



Annex C

Campus scenario calculations

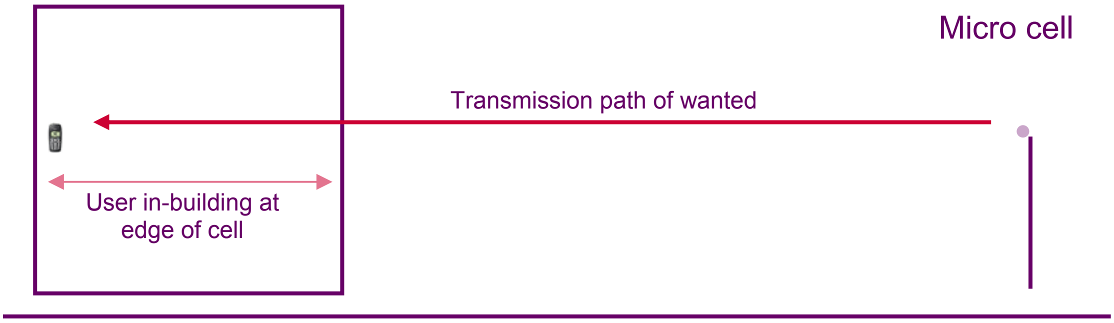
An initial assessment is made to check the probability of call success when using an outdoor micro cell to provide service inside a building. Then the interference from an outdoor micro cell into a victim in-building pico cell system is modelled, for the cases when the interfering micro cell is line of sight and non-line of sight.

Outdoor micro cell providing service inside a building

This model considers an external micro cell providing service to users inside a nearby building. The scenario is valid for the case where the traffic requirements are significantly lower than those modelled in Annex A. The objective is to determine whether it is feasible to provide in-building service in this way and how close to the building the micro cell would need to be for a range of micro cell powers.

The isolation value calculated from the minimum coupling loss method is used, with additional losses in the transmission path. The transmission losses are free space path loss, window penetration loss and in-building penetration loss. This calculation does not consider co-channel interference.

Figure C.1: Wanted signal path



Propagation models

The propagation models used in this annex are: the free space path loss, in-building propagation loss (as used in Annex A and B) and in-building penetration losses (as used in Annex B).

The free space path loss model:

$$L_{FreeSpace} = 20 \log_{10} f + 20 \log_{10} d - 28$$

The in-building propagation loss equation from Recommendation ITU-R P.1238-3:

$$L_{Inbuilding} = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 + 4$$

The in-building penetration losses:

$$L_{BuildingOnly} = L_{Inbuilding} - L_{FreeSpace} = 10 \log_{10} d + 0.4d + 4$$

Figure C.2: Breakdown of the calculation of the transmission path of the wanted signal

The user is placed inside the building at distances of 30m and 40m from the front of the building and the loss inside the building to this point is calculated. Margins of 10.01dB and 14.63dB are assumed in order to give call success probabilities of 90% and 97% respectively. The calculated losses are shown in Tables C.1 and C.2.

Table C.1: System losses for 90% call success

	In building penetration loss, dB	*** Additional margin to yield 90% call success, dB**	**Total loss accounted for, dB**
30m inside building	27.98	10.01	37.99
40m inside building	33.44	10.01	43.45
50m inside building	38.53	10.01	48.54

* The shadow fading of the signal path is assumed to behave consistently with a Gaussian distribution and have a standard deviation of 7.7dB (value given because of mixed path). There 90% success rate is equivalent to 1.3 x standard deviation, or 10.01dB.

Table C.2 System losses for 97% call success

	In building penetration loss, dB $L_{BuildingOnly}$	**Additional margin to yield 97% call success, dB**	**Total loss accounted for, dB**
30m inside building	27.98	14.63	42.61
40m inside building	33.44	14.63	48.07
50m inside building	38.53	14.63	53.16

* The shadow fading of the signal path is assumed to behave consistently with a Gaussian distribution and have a standard deviation of 7.7dB (value given because of mixed path). There 97% success rate is equivalent to 1.9 x standard deviation, or 14.63dB.

The free space loss outside the building is added and the maximum distance between the micro cell and the user's terminal is calculated. This is also converted to a distance between the building and the micro cell. Distances are shown in Tables C.3 and C.4.

Table C.3: Maximum serving distance between micro cell and outside of the wanted building for 90% call success.

EIRP of micro cell, dBm	Penetration distance in-building, m	Receiver sensitivity of user terminal, dBm	Total loss accounted for, dB	Remaining loss, dB	Maximum distance between micro cell and user terminal, m	Maximum distance between micro cell and outside of building, m
23	30	-102	37.99	87.01	284.6	254.6
23	40	-102	43.45	81.55	151.8	111.8
23	50	-102	48.54	76.46	84.5	34.5
26	30	-102	37.99	90.01	402.0	372.0
26	40	-102	43.45	84.55	214.4	174.4
26	50	-102	48.54	79.46	119.3	69.3
30	30	-102	37.99	94.01	637.2	607.2
30	40	-102	43.45	88.55	339.8	299.8
30	50	-102	48.54	83.46	189.1	139.1

Table C.4. Maximum serving distance between micro cell and outside of the wanted building for 97% call success.

EIRP of micro cell, dBm	Penetration distance in-building, m	Receiver sensitivity of user terminal, dBm	Total loss accounted for, dB	Remaining loss, dB	Maximum distance between micro cell and user terminal, m	Maximum distance between micro cell and outside of building, m
23	30	-102	42.61	82.39	167.2	137.2
23	40	-102	48.07	76.93	89.2	49.2
23	50	-102	53.16	71.84	49.6	N/A
26	30	-102	42.61	85.39	236.2	206.2
26	40	-102	48.07	79.93	126.0	86.0
26	50	-102	53.16	74.84	70.1	20.1
30	30	-102	42.61	89.39	374.3	344.3
30	40	-102	48.07	83.93	199.6	159.6
30	50	-102	53.16	78.84	111.1	61.1

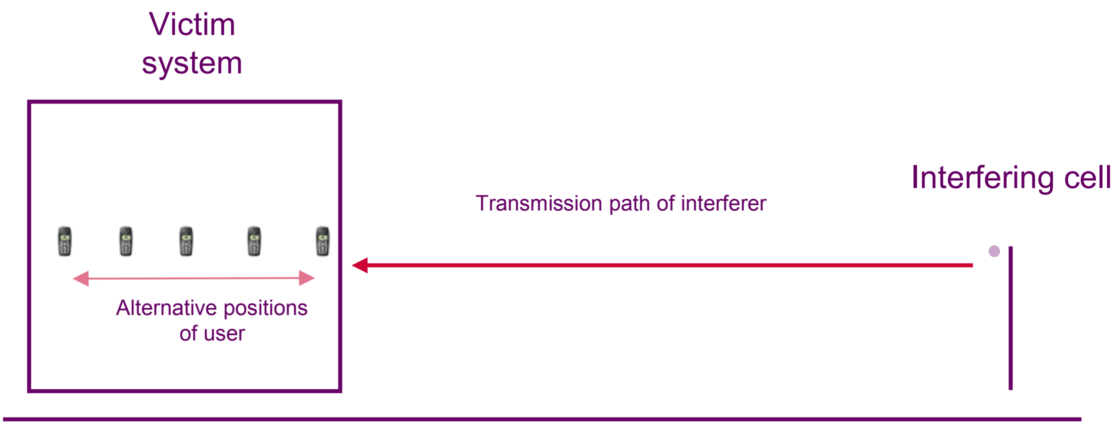
These results show that a 23dBm micro cell could provide service about 40m inside a building with 97% probability of call success or 50m inside the building for 90% probability of call success.

Assessing the potential interference risks from the outdoor micro cell to a victim in-building pico cell

An in-building pico cell has the risk of receiving interference from an external microcell. This campus scenario was modelled in two parts. Campus scenario 1 was modelled with an interfering micro cell having a line of sight path into a victim building. Campus scenario 2 was modelled having a non line of sight path into a victim building, with both one and two intermediate buildings. For both scenarios the probability of call success was assessed for different transmit powers of the micro cell and different separation distances.

Scenario 1: Line of sight scenario

Figure C.3. Interfering signal path



Propagation models

The propagation models used in this annex are: the free space path loss, in-building propagation loss (as used in Annex A and B), and in-building penetration losses (as used in Annex B).

The free space path loss model:

$$L_{FreeSpace} = 20 \log_{10} f + 20 \log_{10} d - 28$$

The in-building propagation loss equation from Recommendation ITU-R P.1238-3:

$$L_{Inbuilding} = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 + 4$$

The in-building penetration losses (as used in Annex B):

$$L_{BuildingOnly} = L_{Inbuilding} - L_{FreeSpace} = 10 \log_{10} d + 0.4d + 4$$

Calculating wanted signal from serving pico cell in own building

A single 23dBm pico cell with a serving radius of 50m is considered. For the purposes of this calculation the coverage is broken into concentric rings at 10m, 20m, 30m, 40m or 50m from the transmitter. The user is placed at the mid-point between each ring and the signal level is calculated. This is illustrated in Figure B.1 where the user in the 10 – 20m ring a distance of 15m is used in the propagation calculations.

Figure C.4. Distance of user from wanted transmitter

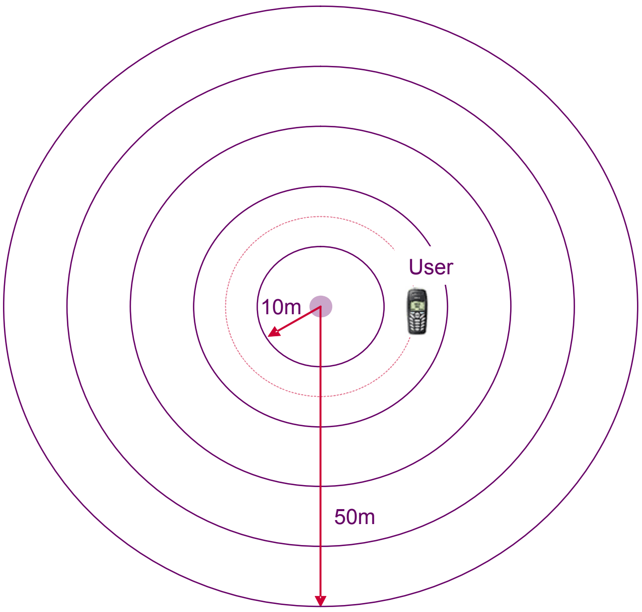


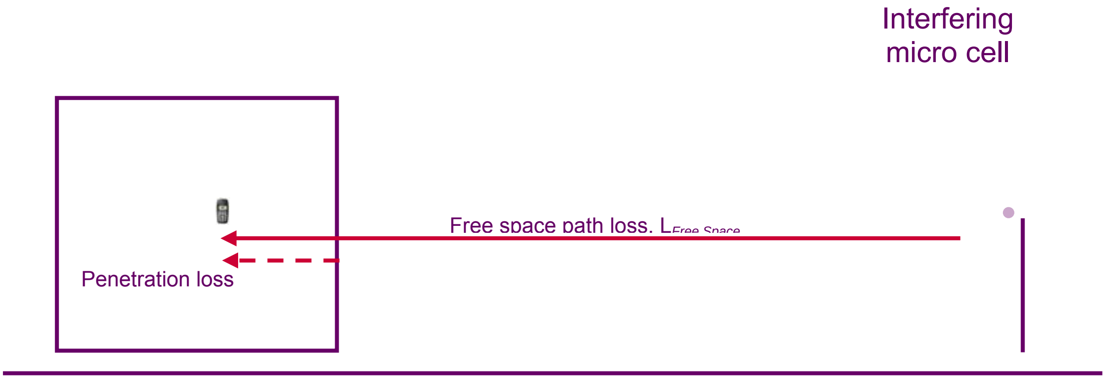
Table C.5 gives the calculated interference levels that can be tolerated based on a 23dBm pico cell base station based on the in-building propagation loss equation, $L_{Inbuilding}$.

Table C.5: Received signal levels from a 23dBm pico cell base station

Distance from pico cell, m	Path loss in building, dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
0-10	71.5	-37.5	9	-46.5
10-20	84.5	-55.8	9	-64.8
20-30	93.8	-66.4	9	-75.4
30-40	101.5	-74.8	9	-83.8
40-50	108.5	-82.1	9	-91.1

Calculating interfering signal into the victim building

Figure C.5. Breakdown of the calculation of the transmission path of interferer



The wanted pico cell and user can be positioned anywhere within the building, varying the potential total length of the interfering path and the likely received interfering signal. Table C.6 shows the in-building penetration loss for various positions of the victim receiver.

Table C.6: Penetration loss in the victim building

Distance of user from window in victim building, m	**Penetration loss, dB ($L_{BuildingOnly}$)**
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

The mean penetration loss due to positional variations, $\overline{X}$ = 26.94dB

The sample standard deviation of data in a sample is calculated by:

Standard deviation = $\sqrt{\frac{1}{n-1}\sum_{i-1}^{n}(X_i - \overline{X})^2}$

The standard deviation calculated is 9.99dB. This represents the variation of penetration loss due to different placements of the victim user terminal.

There are additional variations to consider due to shadowing when modelling variation in the received signals, these are assumed to be:

- 10dB from the wanted transmitter to the user, from Recommendation ITU-R P.1238-3
- 7.7dB from the interfering signal, due to its mixed propagation path.

The total standard deviation for the entire path = $\sqrt{10^2 + 7.7^2 + 9.99^2}$ = 16.10

The mean interfering signal received by the user is calculated by the addition of free space path loss plus the mean in-building loss due to positional variations of the interfering transmitter and a 6dB fast fading margin.

Tables C.7, C.8 and C.9 give the calculated interfering signal levels from 23dBm, 26dBm and 30dBm micro cells.

Table C.7: Mean interfering signal level in victim building from 23dBm micro cell

Total distance between user and interfering cell, km	Transmit power of interfering pico cell, dBm	Free space path loss, dB	Mean in-building penetration loss, dB	Fast fading margin, dB	Mean interfering signal received by user, dBm
0.5	23	91.5	26.9	6	-89.4
1	23	97.5	26.9	6	-95.4
2	23	103.5	26.9	6	-101.4
4	23	109.5	26.9	6	-107.5
6	23	113.0	26.9	6	-111.0
8	23	115.5	26.9	6	-113.5
10	23	117.5	26.9	6	-115.4

Table C.8: Mean interfering signal level in victim building from 26dBm micro cell

Total distance between user and interfering cell, km	Transmit power of interfering pico cell, dBm	Free space path loss, dB	Mean in-building penetration loss, dB	Fast fading margin, dB	Mean interfering signal received by user, dBm
0.5	26	91.46	26.94	6	-86.4
1	26	97.48	26.94	6	-92.4
2	26	103.50	26.94	6	-98.4
4	26	109.52	26.94	6	-104.5
6	26	113.05	26.94	6	-108.0
8	26	115.54	26.94	6	-110.5
10	26	117.48	26.94	6	-112.4

Table C.9: Mean interfering signal level in victim building from 30dBm micro cell

Total distance between user and interfering cell, km	Transmit power of interfering pico cell, dBm	Free space path loss, dB	Mean in-building penetration loss, dB	Fast fading margin, dB	Mean interfering signal received by user, dBm
0.5	30	91.46	26.94	6	-82.4
1	30	97.48	26.94	6	-88.4
2	30	103.50	26.94	6	-94.4
4	30	109.52	26.94	6	-100.5
6	30	113.05	26.94	6	-104.0
8	30	115.54	26.94	6	-106.5
10	30	117.48	26.94	6	-108.4

Calculating the likelihood of call success

Tables C.10, C.11 and C.12 show the total probability of a successful call and are derived by taking the probability of a successful call multiplying by the proportion of users. These values are added together to find the total probability of a call success.

Table C.10: Total probability of call success for the 23dBm micro cell interferer

	Proportion of successful calls						
Distance of user from own pico cell, m	**Distance of the interfering transmitter from the victim user**						
	0.5km	**1km**	**2km**	**4km**	**6km**	**8km**	**10km**
0 - 10	0.04	0.04	0.04	0.04	0.04	0.04	0.04
10 - 20	0.11	0.12	0.12	0.12	0.12	0.12	0.12
20 - 30	0.16	0.18	0.19	0.20	0.20	0.20	0.20
30 - 40	0.18	0.21	0.24	0.26	0.27	0.27	0.27
40 - 50	0.17	0.22	0.27	0.30	0.32	0.33	0.34
Total probability	0.66	0.77	0.86	0.92	0.95	0.96	0.97

Table C.11: Total probability of call success for the 26dBm micro cell interferer

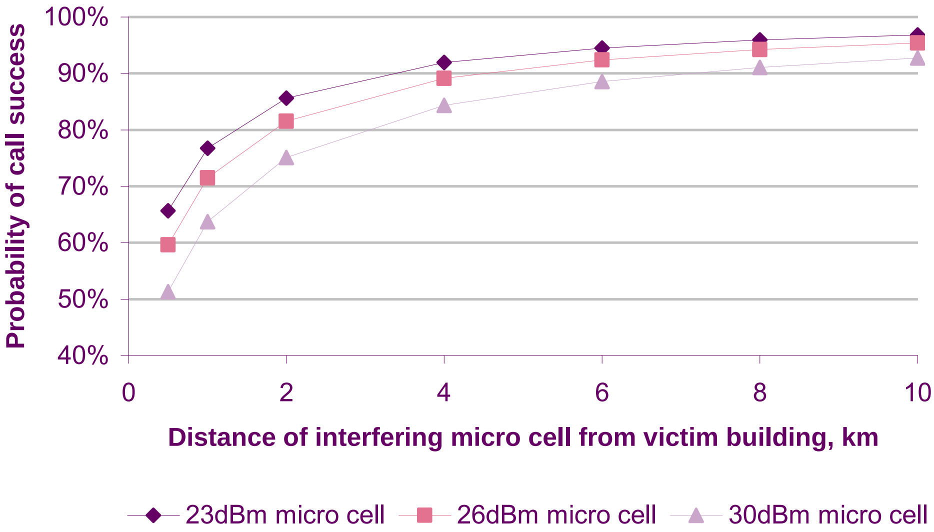
	Proportion of successful calls						
Distance of user from own pico cell, m	**Distance of the interfering transmitter from the victim user**						
	0.5km	**1km**	**2km**	**4km**	**6km**	**8km**	**10km**
0 - 10	0.04	0.04	0.04	0.04	0.04	0.04	0.04
10 - 20	0.11	0.11	0.12	0.12	0.12	0.12	0.12
20 - 30	0.15	0.17	0.18	0.19	0.20	0.20	0.20
30 - 40	0.16	0.20	0.23	0.25	0.26	0.27	0.27
40 - 50	0.14	0.19	0.24	0.29	0.31	0.32	0.33
Total probability	0.60	0.71	0.82	0.89	0.92	0.94	0.95

Table C.12: Total probability of call success for the 30dBm micro cell interferer

	Proportion of successful calls						
Distance of user from own pico cell, m	**Distance of the interfering transmitter from the victim user**						
	0.5km	**1km**	**2km**	**4km**	**6km**	**8km**	**10km**
0 - 10	0.04	0.04	0.04	0.04	0.04	0.04	0.04
10 - 20	0.11	0.11	0.12	0.12	0.12	0.12	0.12
20 - 30	0.14	0.16	0.17	0.18	0.19	0.19	0.20
30 - 40	0.13	0.17	0.20	0.21	0.23	0.24	0.26
40 - 50	0.10	0.15	0.19	0.21	0.24	0.27	0.31
Total probability	0.51	0.64	0.72	0.76	0.82	0.86	0.93

These results are shown graphically in Figure C.6.

Figure C.6. Probability of call success



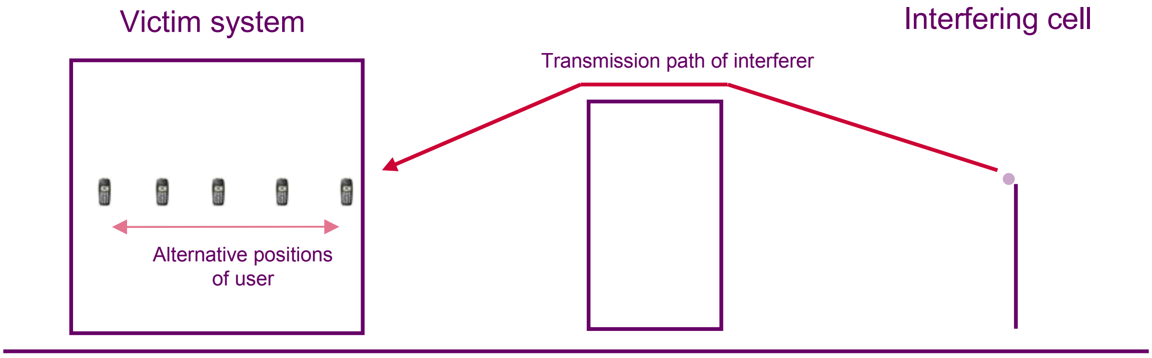
The service from an indoor pico cell suffered greatly from co-channel interference, when the interfering micro cell is within line of site. To achieve a 90% probability of call success, if within line of site, a 23dBm micro cell would have to be over 3km away to avoid co-channel interference. To achieve a 97% probability of call success, if within line of site, a 23dBm micro cell would have to be 10km away to avoid co-channel interference. This result indicates that if a potential victim system is vulnerable within a large area if it is within line-of-sight of an external micro cell.

A restriction on the maximum antenna height of an external micro cell could be a means of reducing the probability of victim systems being within line-of-sight and therefore suffering from unacceptable interference.

Campus scenario 2a: Non-line of sight scenario with a single intermediate building

This scenario models the effect of an external interfering micro cell when there is a single intermediate building in the path of the interference. The interfering micro cell is below the height of the surrounding clutter, with the micro cell transmitter height 10m high and the intermediate building assumed to be 15m high.

Figure C.7. Interfering signal path



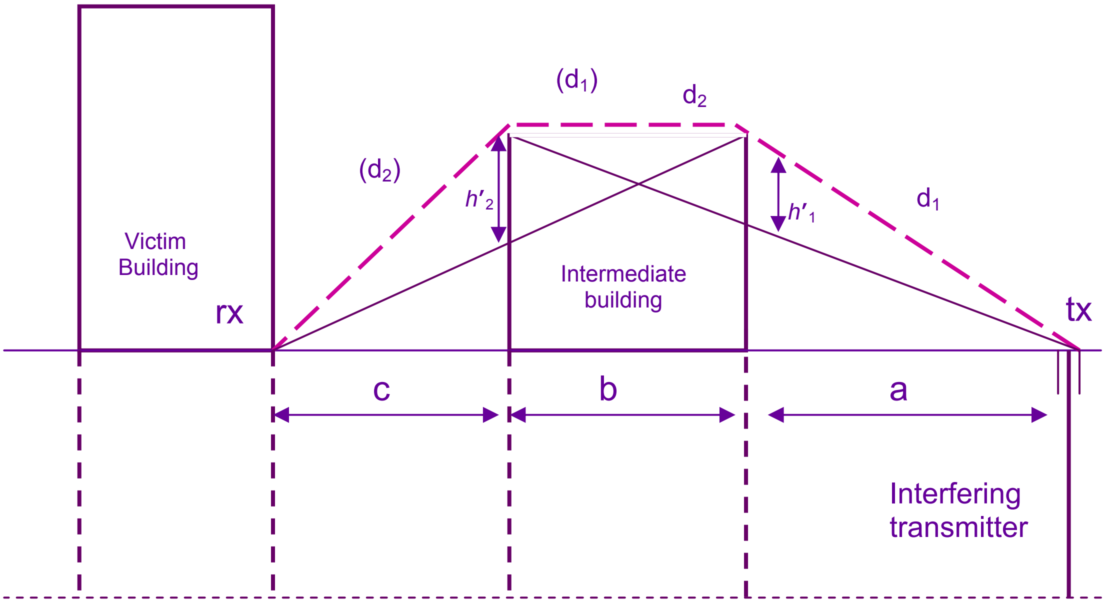
Diffraction loss over intermediate building

The diffraction loss was calculated in accordance with Recommendation ITU-R P.526-8 and used the method for 'double isolated edges'.

This method consists of applying single knife-edge diffraction theory successively to the two edges of the building, with the top of the first edge acting as a source for diffraction over the second edge (see Figure C.8).

The first diffraction path, defined by the distances *a* and *b* and the height h'_1 gives a loss L_1 (dB). The second diffraction path, defined by the distances *b* and *c* and the height h'_2 gives a loss L_2 (dB).

Figure C.8. Use of the double isolated edges method from P.526-8 to calculate diffraction over the intermediate building



Losses L_1 and L_2 were calculated by first calculating an intermediate variable, ν :

$$\nu = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} \qquad (1)$$

The diffraction loss in dB for L_1 and L_2, is then found by the equation:

$$J(\nu) = 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right) \quad \text{dB} \qquad (2)$$

A correction term L_c (dB) must be added if both L_1 and L_2 are in excess of 15dB..

L_c may be estimated by the following formula:

$$L_c = 10\log\left[\frac{(a + b)\ (b + c)}{b\,(a + b + c)}\right]$$

The total diffraction loss is then given by:
$L = L_1 + L_2 + L_c$

Example calculation.

Parameters:

Building height	15m
Building width	30m (distance b)
Transmitter height	10m
Distance between micro cell and wanted building (distance a)	100 m
Distance between wanted building and victim building (distance c)	50m

Wavelength at 1880 MHz is 0.16m.

Calculation for diffraction loss L_1

$$d_1 = \sqrt{a^2 + Buildingheight^2} = \sqrt{100^2 + 15^2} = 100.12$$

$$d_2 = 30$$

$$h'1 = (Buildingheight - txheight)\left(\frac{b}{d_1 + b}\right) = 5.\left(\frac{30}{100.12 + 30}\right) = 1.153$$

$$v = h'1.\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} = 1.153\sqrt{\frac{2}{0.16}\left(\frac{1}{100.12} + \frac{1}{30}\right)} = 0.85$$

And the loss (L_1) in dB is found by

$$J(v) = 6.9 + 20\log\left(\sqrt{(v - 0.1)^2 + 1} + v - 0.1\right)$$
$$= 6.9 + 20\log\left(\sqrt{(0.85 - 0.1)^2 + 1} + 0.85 - 0.1\right) = 12.92dB$$

Calculation for diffraction loss L_2

$$d_1 = 30$$

$$d_2 = \sqrt{Buildingheight^2 + c^2} = \sqrt{15^2 + 50^2}$$

$$h'_2 = (Buildingheight - txheight)\left(\frac{b}{d_1 + b}\right) = 5.\left(\frac{30}{100.12 + 30}\right) = 1.875$$

$$v = h'2.\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} = 1.875\sqrt{\frac{2}{0.16}\left(\frac{1}{30} + \frac{1}{50.25}\right)} = 1.53$$

And the loss (L_2) in dB is found by

$$J(\nu) = 6.9 + 20 \log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right)$$

$$= 6.9 + 20 \log\left(\sqrt{(1.53 - 0.1)^2 + 1} + 1.53 - 0.1\right) = 16.93dB$$

Correction factor for loss between diffraction edges L_c

As stated in ITU-R P.526-8, if L_1 and L_2 both exceed 15dB, an additional loss is to be accounted for by a correction factor L_c, so total diffraction loss becomes $L_1 + L_2 + L_c$.

$$L_c = 10 \log\left[\frac{(a + b)\ (b + c)}{b\,(a + b + c)}\right]$$

Calculating wanted signal from serving pico cell in own building

A single 23dBm pico cell with a serving radius of 50m is considered. For the purposes of this calculation the coverage is broken into concentric rings at 10m, 20m, 30m, 40m or 50m from the transmitter. The user is placed at the mid-point between each ring and the signal level is calculated.

Table C.13: Received signal levels from a 23dBm pico cell base station

Distance from pico cell, m	Path loss in building, dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
0 - 10	71.5	-37.5	9	-46.5
10 - 20	84.5	-55.8	9	-64.8
20 - 30	93.8	-66.4	9	-75.4
30 - 40	101.5	-74.8	9	-83.8
40 - 50	108.5	-82.1	9	-91.1

Calculating interfering signal into the victim building

In order to calculate the interference power from the interfering micro cell onto the victim building, the total path loss was calculated. The total path loss comprised of the diffraction loss caused by the intermediate building plus the free space loss between the interfering cell and the victim building. Note that diffraction around the sides of the building was not considered.

Figure C.9. Breakdown of the calculation of the transmission path of interferer

The user can be positioned anywhere within the building, varying the potential total length of the interfering path and the likely received interfering signal. Table C.14 shows the in-building penetration loss for various positions of the victim receiver.

Table C.14: Penetration loss in victim building

Distance of user from window in victim building, m	Penetration loss, dB ($L_{BuildingOnly}$)
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

The mean penetration loss, $\overline{X}$ = 26.94dB

The standard deviation calculated is 9.99dB. This represents the variation of penetration loss due to different placements of the victim user terminal.

There are additional variations to consider due to shadowing when modelling variation in the received signals, these are assumed to be:

- 10dB from the wanted transmitter to the user, from Recommendation ITU-R P.1238-3
- 7.7dB from the interfering signal, from its mixed propagation path.
- 7.7dB diffraction over the intermediate building

The total standard deviation for the entire path =

$$\sqrt{10^2 + 7.7^2 + 7.7^2 + 9.99^2} = 17.84$$

The mean interfering signal received by the user is calculated by the addition of free space path loss, the diffraction loss over the intermediate building, plus the mean in-building loss due to positional variations of the interfering transmitter and 6dB fast fade margin.

The mean interfering signal was considered with the following building separation distances outlined in Table C.15.

Table C.15: Total separation distance between interfering transmitter and the victim user

Distance between the victim user and intermediate building, m	Width of intermediate building, m	Distance between intermediate building and interfering transmitter, m	Total distance between the interfering transmitter and the victim user, m
50	30	50	**130**
50	30	100	**180**
50	30	200	**280**
50	30	500	**580**
50	30	700	**780**

Table C.16: Mean interfering signal level in victim building from 23dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate building, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
130	26.94	36.0	82.61	142.8	6	-113.77
180	26.94	29.9	84.73	139.4	6	-110.41
280	26.94	26.8	87.86	140.2	6	-111.22
580	26.94	24.6	91.97	144.3	6	-115.31
780	26.94	24.2	94.75	146.4	6	-117.42

Table C.17: Mean interfering signal level in victim building from 26dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate building, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
130	26.94	36.0	82.61	142.8	6	-110.77
180	26.94	29.9	84.73	139.4	6	-107.41
280	26.94	26.8	87.86	140.2	6	-108.22
580	26.94	24.6	91.97	144.3	6	-112.31
780	26.94	24.2	94.75	146.4	6	-114.42

Table C.18: Mean interfering signal level in victim building from 30dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate building, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
130	26.94	36.0	82.61	142.8	6	-106.77
180	26.94	29.9	84.73	139.4	6	-103.41
280	26.94	26.8	87.86	140.2	6	-104.22
580	26.94	24.6	91.97	144.3	6	-108.31
780	26.94	24.2	94.75	146.4	6	-110.42

Calculating the likelihood of call success

Tables C.19, C.20 and C.21 show the total probability of a successful call and are derived by taking the probability of a successful call multiplying by the proportion of users. These values are added together to find the total probability of a call success.

Table C.19: Total probability of call success for the 23dBm micro cell interferer

	Proportion of successful calls				
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user, m				
	130	180	280	580	780
0 - 10	0.04	0.04	0.04	0.04	0.04
10 - 20	0.12	0.12	0.12	0.12	0.12
20 - 30	0.20	0.20	0.20	0.20	0.20
30 - 40	0.27	0.26	0.27	0.27	0.27
40 - 50	0.33	0.32	0.32	0.33	0.34
Total probability	0.96	0.94	0.94	0.96	0.97

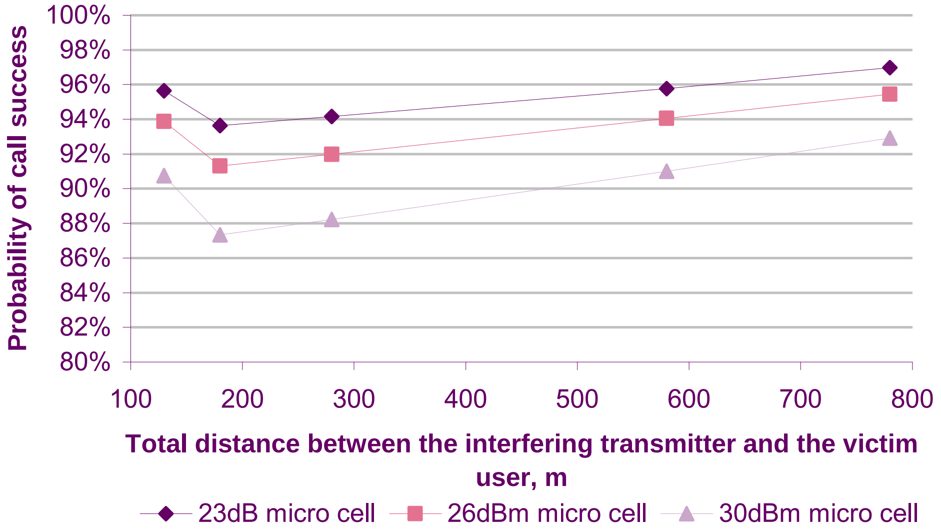
Table C.20: Total probability of call success for the 26dBm micro cell interferer

	Proportion of successful calls				
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user, m				
	130	180	280	580	780
0 - 10	0.04	0.04	0.04	0.04	0.04
10 - 20	0.12	0.12	0.12	0.12	0.12
20 - 30	0.20	0.19	0.20	0.20	0.20
30 - 40	0.27	0.26	0.26	0.27	0.27
40 - 50	0.32	0.30	0.31	0.32	0.33
Total probability	0.94	0.91	0.92	0.94	0.95

Table C.21: Total probability of call success for the 30dBm micro cell interferer

Distance of user from own pico cell, m	Proportion of successful calls				
	Distance of the interfering transmitter from the victim user, m				
	130	180	280	580	780
0 - 10	0.04	0.04	0.04	0.04	0.04
10 - 20	0.12	0.12	0.12	0.12	0.12
20 - 30	0.19	0.19	0.19	0.19	0.20
30 - 40	0.26	0.25	0.25	0.26	0.26
40 - 50	0.30	0.28	0.28	0.30	0.31
Total probability	0.91	0.87	0.88	0.91	0.93

Figure C.11. Probability of call success with an intermediate building between the micro cell and victim receiver



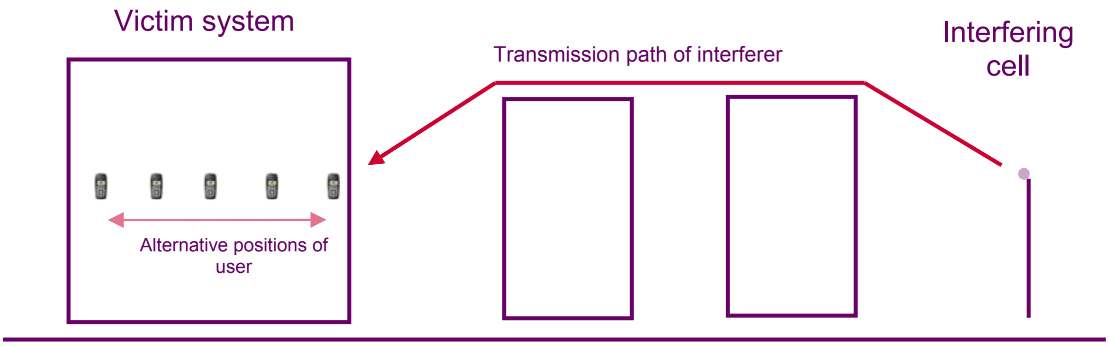
The mean interfering signal was considered with the building separation distances outlined in Table C.15. The variation in the result accounts for the combination of the effect of the free space path loss over the intermediate building and the diffraction over the building. The loss due to diffraction over the intermediate building decreased as the interfering transmitter was modelled a greater distance away; however the loss due to free space path loss increased as the interfering transmitter was modelled a greater distance away.

The worst case modelled was an 87% call success rate with the 30dBm micro cell interferer, when the total distance between the interfering transmitter and the victim user was 180m. The 23dBm micro cell results reached a minimum of 94%. A call success rate of 97% was achieved when the 23dBm micro cell was 780m from the building. In a separation of 780m between an interfering micro cell and a victim in-building pico cell, there may be more than one intermediate building. Additional buildings and clutter will further attenuate the affect of the interfering signal and increase the likelihood of call success in the victim building. Campus scenario 2b models the affect of two intermediate buildings in the interference path.

Campus scenario 2b: Non-line of sight scenario with a two intermediate buildings

This scenario models the effect of an external interfering micro cell when there are two intermediate buildings in the path of the interferer.

Figure C.10. Interfering signal path



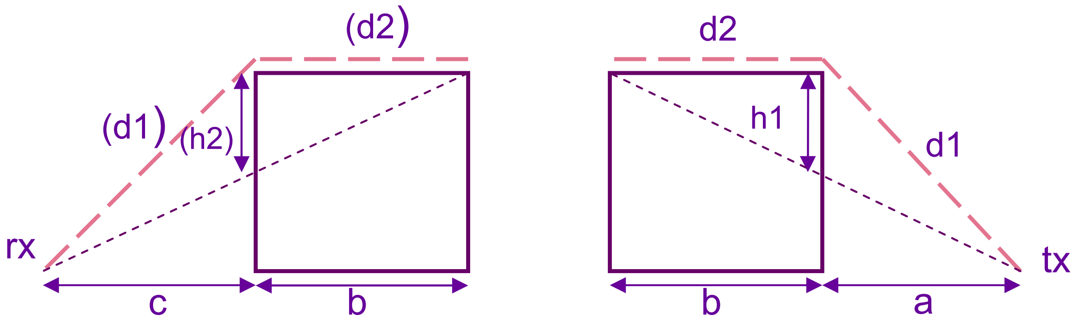
Diffraction loss over two intermediate buildings

The diffraction loss was calculated in accordance with Recommendation ITU-R P.526-8 and used the method for ‘double isolated edges’, as used previously in this annex for diffraction loss over one intermediate building.

This method consists of applying single knife-edge diffraction theory successively to the two edges of the building, with the top of the first edge acting as a source for diffraction over the second edge (see Figure C.8).

The first diffraction path, defined by the distances *a* and *b* and the height h_1 gives a loss L_1 (dB). The second diffraction path, defined by the distances *b* and *c* and the height h_2 gives a loss L_2 (dB).

Figure C.11. Use of the double isolated edges method from P.526-8 to calculate diffraction over the intermediate buildings



The additional building edges in the transmission path would generate losses and a further 6dB diffraction loss was assumed.

Calculating interfering signal into the victim building

In order to calculate the interference power from the interfering micro cell onto the victim building, the total path loss was calculated.

The mean interfering signal received by the user is calculated by the addition of free space path loss, the diffraction loss over the intermediate buildings, plus the mean in-building loss due to positional variations of the interfering transmitter and 6dB fast fade margin. Note that diffraction around the sides of the building was not considered.

The mean interfering signal was considered with the following building separation distances outlined in Table C.22.

Table C.22: Total separation distance between interfering transmitter and the victim user

Distance between the victim user second intermediate building, m	Width of intermediate buildings, m	Distance between buildings, m	Distance between first intermediate building and interfering transmitter, m	Total distance between the interfering transmitter and the victim user, m
50	30	30	50	**190**
50	30	30	100	**240**
50	30	30	200	**340**
50	30	30	300	**440**
50	30	30	400	**540**

Table C.23: Mean interfering signal level in victim building from 23dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate buildings, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
190	26.94	42.04	81.59	150.57	6	-121.57
240	26.94	35.86	83.94	146.75	6	-117.75
340	26.94	32.84	87.32	147.10	6	-118.10
440	26.94	31.64	89.74	148.32	6	-119.32
540	26.94	31.00	91.64	149.58	6	-120.58

Table C.24: Mean interfering signal level in victim building from 26dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate buildings, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
190	26.94	42.04	81.59	150.57	6	-118.57
240	26.94	35.86	83.94	146.75	6	-114.75
340	26.94	32.84	87.32	147.10	6	-115.10
440	26.94	31.64	89.74	148.32	6	-116.32
540	26.94	31.00	91.64	149.58	6	-117.58

Table C.25: Mean interfering signal level in victim building from 30dBm micro cell

Total distance between micro cell and victim building, m	Mean in-building penetration loss, dB	Diffraction over intermediate buildings, dB	Free space path loss, dB	Total losses, dB	Fast fade margin, dB	Mean interfering signal, dBm
190	26.94	42.04	81.59	150.57	6	-114.57
240	26.94	35.86	83.94	146.75	6	-110.75
340	26.94	32.84	87.32	147.10	6	-111.10
440	26.94	31.64	89.74	148.32	6	-112.32
540	26.94	31.00	91.64	149.58	6	-113.58

Calculating the likelihood of call success

Tables C.26, C.27 and C.28 show the total probability of a successful call and are derived by taking the probability of a successful call multiplying by the proportion of users. These values are added together to find the total probability of call success. The total standard deviation for the entire path is assumed to be 17.84, as calculated for the scenario for the single intermediate building.

Table C.26: Total probability of call success for the 23dBm micro cell interferer

	Proportion of successful calls				
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user, m				
	190	240	340	440	540
0 - 10	0.040	0.040	0.040	0.040	0.040
10 - 20	0.120	0.120	0.120	0.120	0.120
20 - 30	0.199	0.198	0.198	0.199	0.199
30 - 40	0.275	0.272	0.272	0.273	0.275
40 - 50	0.344	0.336	0.337	0.340	0.342
Total probability	0.978	0.966	0.967	0.972	0.976

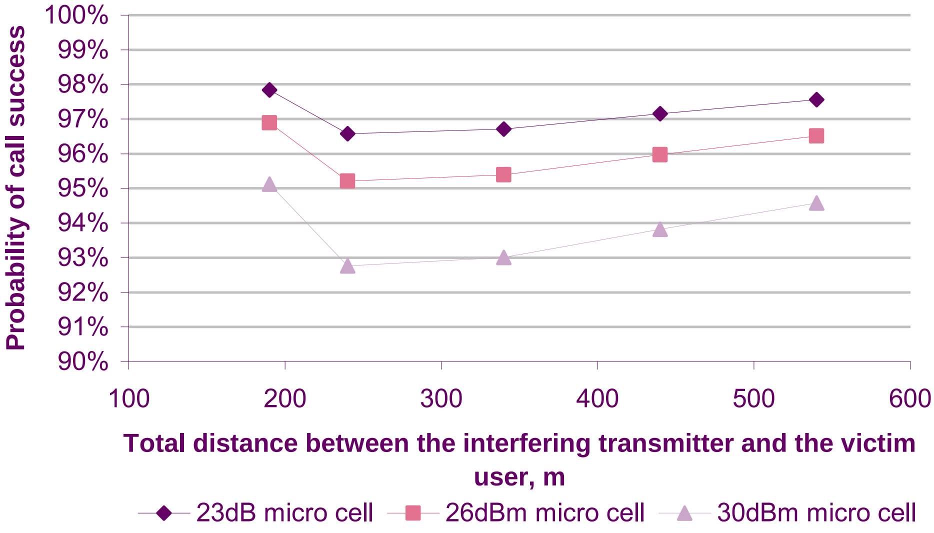
Table C.27: Total probability of call success for the 26dBm micro cell interferer

	Proportion of successful calls				
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user, m				
	190	**240**	**340**	**440**	**540**
0 - 10	0.040	0.040	0.040	0.040	0.040
10 - 20	0.120	0.120	0.120	0.120	0.120
20 - 30	0.198	0.197	0.197	0.198	0.198
30 - 40	0.273	0.268	0.269	0.270	0.272
40 - 50	0.338	0.327	0.328	0.332	0.335
Total probability	0.969	0.952	0.954	0.960	0.965

Table C.28: Total probability of call success for the 30dBm micro cell interferer

	Proportion of successful calls				
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user, m				
	190	**240**	**340**	**440**	**540**
0 - 10	0.040	0.040	0.040	0.040	0.040
10 - 20	0.120	0.119	0.119	0.120	0.120
20 - 30	0.197	0.195	0.195	0.196	0.197
30 - 40	0.268	0.262	0.262	0.265	0.267
40 - 50	0.326	0.311	0.313	0.318	0.323
Total probability	0.951	0.928	0.930	0.938	0.946

Figure C.12. Probability of call success with a two intermediate buildings between the micro cell and victim receiver



For scenario 2b, where there are two intermediate buildings, the worst case modelled was 93% call success rate with the 30dBm micro cell interferer, when the total distance between the interfering transmitter and the victim user was 240m. A call success rate of 97% was achieved when the 23dBm micro cell was 190m, 440m and 540m from the wanted building. The 23dBm micro cell results reached a minimum of 96.6%. This is a significant improvement in the results calculated for scenario 2a with a single intermediate building, where a call success rate of 97% was achieved for the 23dBm micro cell at a total separation distance of 780m.

The results indicate that building clutter is very effective at limiting co-channel interference and that inadvertent interference to a victim system is significantly reduced, if the interfering transmitter height is below the level of surrounding clutter. Therefore a restriction on the maximum antenna height of an external micro cell would reduce probability of interference between systems.

Annex D

Residential scenario

Two deployment scenarios are modelled in this section. The first models the frequency re-use factor within a row of terraced houses when a 0dBm GSM pico cell is installed in each house. The second scenario models the potential for interference between houses across a street.

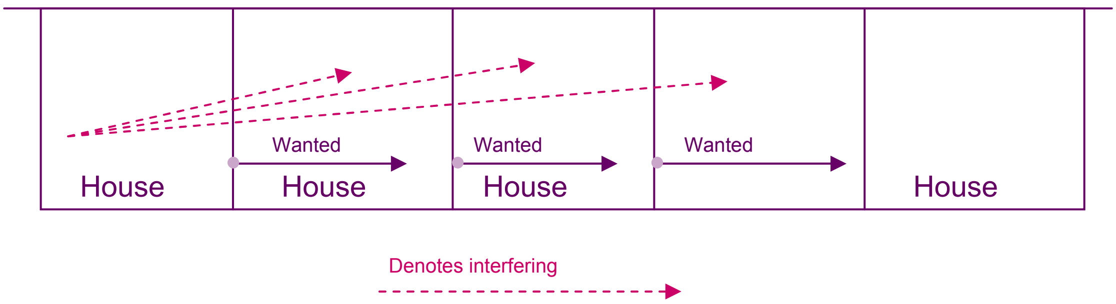
Scenario 1: Frequency re-use between a row of houses

Modelling for this scenario was accomplished using the same general methods described in the preceding annex's, i.e. a signal is assumed to suffer interference when the ratio of wanted signal to interfering signal is less than the minimum carrier-to-interference (C/I) ratio specified for the system. Both of these signals suffer variability and normally Monte Carlo modelling is used to overcome the problems created by the twin sources of variability. Fortunately, if both sources of variability are assumed to be Gaussian, it is possible to take the standard deviations from both the wanted and interfering path and to apply this to obtain the margin above minimum C/I and then calculate the probability of call success.

For this particular scenario, both the interferer house and the victim house were partitioned into five areas. It is assumed that there is an equal probability that a transmitter or user would be positioned within these areas. This gives a total of twenty five possible distances between the wanted signal path and the unwanted (interfering) signal path. The wanted and unwanted signal strengths were then calculated for all twenty five possible distances by varying the distance between the interferer and victim, i.e. one house separation is 5m, two house separation is 10m, etc. The results were then used to calculate the margin above C/I for each value. As before, the normalised variable Z was calculated from the root sum of squares of the standard deviation for fading, and the results average to find the probability of call success.

The method was used to calculate the probability of call success for the first house from the interferer, the second house from the interferer, third house etc until a successful call probability value of above 97% was reached.

Figure D.1. Frequency re-use scenario



House dimensions.
A typical terraced house is assumed to have the following dimensions:
Width = 5 m
Depth = 8m
Height = 11 m

Propagation models

The in-building propagation loss equation from Recommendation ITU-R P.1238-3:

Within the building the field strength will be reduced by diffraction, where the first Fresnel zone is obstructed (due to building layout and furniture). Recommendation ITU-R P.1238-3 provides the following equation to calculate the propagation losses within buildings:

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_{floor}(n) - 28 \qquad \text{dB}$$

where:

L_{total} : total propagation loss
N : distance power loss coefficient
f : frequency (MHz)
d : separation distance (m) between the base station and portable terminal (where $d \geq 1$m)
L_{floor} : floor penetration loss factor (dB)
n : number of floors between base station and portable terminal ($n \geq 1$).

Recommendation ITU-R P.1238-3 indicates that the typical value for N within a residential building is 28.

Additional losses are to be included. Recommendation ITU-R P.1238 indicates that a floor penetration loss factor (L_{floor}) of 4dB is applicable to a residential building. For this scenario we assumed a floor at every 5 m distance. For modelling purposes this figure was equated to a per metre distance value, which gives a factor of 0.8 x distance. It was also assumed that there would be an attenuation of 10dB per adjoining wall.

An additional 6dB was added to the interference propagation model to allow for fast fading effects.

The in-building propagation loss equation becomes:

$$L_{wanted} = 20 \log_{10} f + 28 \log_{10} d + 0.8d - 28 \qquad \text{dB}$$

$$L_{unwanted} = 20 \log_{10} f + 28 \log_{10} d + 0.8d - 28 + 10\text{dB per wall} - 6\text{dB} \qquad \text{dB}$$

Pico cell radiated power

The pico cell effective isotropic radiated power was calculated by finding the longest path distance within a house and calculating the total path losses. The loss calculations include a fade margin calculated to ensure 90% probability of call success at the cell edge. Note that this figure yields a 97 % call success rate over the cell area[‡]. In a Gaussian distribution, a 90% probability is achieved within 1.3 standard deviations.

Recommendation ITU-R P.1238 indicates that a standard deviation of 8dB is the requirement for a residential building. The required fade margin was calculated by 1.3 standard deviations x 8dB = 10.4dB.

[‡] W.C. Jakes, Microwave mobile communications, IEEE, New York, published 1994, page 127, figure 2.5-1.

Pico cell EIRP = Rx + fade margin + path loss
= -104 + 10.4 + 80
= -13.6dBm

We conclude that a pico cell of 0dBm is sufficient to give coverage within the residential property.

Distances of transmitter and receiver

The house was partitioned into five areas. It is assumed that there is an equal probability that a transmitter or user would be positioned within these areas. Each of the five areas were equated to a mid point distance by taking the longest path length of a house and dividing by 5. This gives the mid point positions of the pico cells for both victim user and unwanted interferer. Note that since it is assumed that the user will be a minimum of 0.5m distance from the serving cell, the mid point position of a user differs from that of the interfering pico cell by 0.5m .

Mid point calculation

The longest path distance in the building was calculated

$$14.5 = \sqrt{5^2 + 11^2 + 8^2}$$

This distance is divided by 5 to give a diagonal distance for each area.

Therefore mid point diagonal position for pico cell in area 1 is 2.9/2 = 1.45m
Mid point diagonal position for pico cell in area 2 is 1.45 + 2.9 = 4.35m

Mid point diagonal position for victim user in area 1 is 2.9/2 +0.5 = 1.95m
Mid point diagonal position for victim user in area 2 is 1.95 + 2.9 = 4.85m

Mid point diagonal positions for both victim user and interfering pico cell are tabulated below in table D1 for all five areas.

Table D1. Mid point positions for pico cell and user.

	Mid point diagonal position of interfering pico-cell, m	Mid point diagonal position of victim user, m
Area 1	1.45	1.95
Area 2	4.35	4.85
Area 3	7.25	7.75
Area 4	10.14	10.64
Area 5	13.04	13.54

The mid point diagonal positions above are used in the calculation of the wanted and unwanted signal strengths.

Wanted signal strengths were calculated using the propagation model

$$L_{wanted} = 20 \log_{10} f + 28 \log_{10} d + 0.8\, d - 28$$

Example calculation:

$20 \log_{10} 1880 + 28 \log_{10} 1.95 + 0.8 \times 1.95 - 28 = 47.15$

Table D.2, below contains the path loss for the wanted signal for all five areas and also the maximum permitted interference levels.

Table D.2 Received signal levels from a 0dBm pico cell base station.

Distance from pico cell, m	Path loss in building dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
1.95	47.15	-47.15	9.00	-56.15
4.85	60.55	-60.55	9.00	-69.55
7.75	68.57	-68.57	9.00	-77.57
10.64	74.75	-74.75	9.00	-83.75
13.54	80.00	-80.00	9.00	-89.00

The interference path length was calculated by first converting the diagonal distances of the mid point positions in Table D.1 to vertical distances, and then subtracting the difference between each value to find the vertical component.
The horizontal component was given by the separation distance between the wanted signal and the interferer ie, one house length, two house lengths etc. Pythagoras theorem was then used to find the interference path length.

Example calculation based on a separation of third house from the interferer:

$$\tan^{-1}\theta = \frac{o}{a} = 49.38^0$$

Vertical height h1 given by sin 49.38 x 1.45 = 1.10m
Vertical height h2 given by sin 49.38 x 1.95 = 1.48m

Difference between h2 and h1 = 0.38m

Total interference path length = $\sqrt{15^2 + 0.38^2}$
= 15.00m

All Interference paths are shown below in Table D3.

Note that the following example tables D3 – D6 refer to calculations for a separation of the third house from the interferer.

Table D.3. Length of interference path at a separation of 15m (third house from the unwanted signal.

	Length of interference path, m				
Interferer distances	Distance from wanted cell 1.95m	Distance from wanted cell 4.85m	Distance from wanted cell 7.75m	Distance from wanted cell 10.64m	Distance from wanted cell 13.54m
1.45m	15.00	15.22	15.74	16.54	17.59
4.35m	15.11	15.00	15.22	15.74	16.54
7.25m	15.53	15.11	15.00	15.22	15.74
10.14m	16.24	15.53	15.11	15.00	15.22
13.04m	17.20	16.34	15.53	15.11	15.00

The unwanted signal strengths were calculated for all areas by use of

$$L_{unwanted} = 20 \log_{10} f + 28 \log_{10} d + 0.8d - 28 + 30 - 6$$

Example calculation:

$$20 \log_{10} 1880 + 28 \log_{10} 15 + 0.8 \text{ x} 15d - 28 + 30 - 6 = 106.42\text{dB}$$

Unwanted signal strengths were calculated for all areas and tabulated below in D4.

Table D4 Unwanted signal strengths based on third house from interferer separation distance.

	Unwanted signal strengths, dB				
Interferer distances	**Distance from wanted cell 1.95 m**	**Distance from wanted cell 4.85m**	**Distance from wanted cell 7.75m**	**Distance from wanted cell 10.64m**	**Distance from wanted cell 13.54m**
1.45m	-106.42	-106.76	-107.59	-106.84	-110.41
4.35m	-106.59	-106.42	-106.76	-107.59	-106.84
7.25m	-107.26	-108.59	-112.42	-106.76	-107.59
10.14m	-108.36	-107.25	-112.72	-106.42	-106.76
13.04m	-109.84	-108.36	-113.85	-106.59	-106.42

We now derive figures for the margin above the minimum C/I required to make a call by subtracting the interference signal power in Table D4 above from the maximum permitted interference levels in Table D2. The results are shown below in Table D.5

Table D.5 .Margin above minimum C/I.

	Margin above minimum C/I, dB				
Interferer distances	**Distance from wanted cell 1.95 m**	**Distance from wanted cell 4.85m**	**Distance from wanted cell 7.75m**	**Distance from wanted cell 10.64m**	**Distance from wanted cell 13.54m**
1.45m	50.26	37.21	30.02	25.08	21.41
4.35m	50.43	36.87	29.19	23.84	19.83
7.25m	51.10	37.04	28.85	23.01	18.59
10.14m	52.21	37.70	29.02	22.66	17.76
13.04m	53.68	38.81	29.68	22.83	17.42

In order to find the probabilities of signal interference, it was necessary to find the total standard deviation for the wanted and unwanted signals, using the root sum of square method. The 8dB standard deviation values for signal fading were taken from Recommendation ITU-R P.1238.
The total standard deviation is therefore:

$$\sqrt{8^2 + 8^2} = 11.31$$

The standardised normal variable (Z) is the difference between the mean interfering signal and signal to be protected expressed as a number of standard deviations. The Z value was calculated by the division of the total standard deviation value of 11.31 into the values obtained in Table D.4.

Table D.6 below is an interim step, where the standardised normal variable, Z, has been found in order to calculate the probability of a successful call.

Table D.6 Normalised Z values

	Normalised Z value				
Interferer distances	**Distance from wanted cell 1.95 m**	**Distance from wanted cell 4.85m**	**Distance from wanted cell 7.75m**	**Distance from wanted cell 10.64m**	**Distance from wanted cell 13.54m**
1.45m	4.44	3.29	2.65	2.22	1.89
4.35m	4.46	3.26	2.58	2.11	1.75
7.25m	4.52	3.27	2.55	2.03	1.64
10.14m	4.62	3.33	2.57	2.00	1.57
13.04m	4.75	3.43	2.62	2.02	1.54

The result was used to calculate the probability that the desired signal to noise ratio will not be breached. The figures below in table D7 represent the probability of call success based upon 25 positional variations between the wanted and unwanted signal. Therefore an average value is taken which gives an overall probability of call success.

Table D.7. Probability of call success.

	% Probability of call success				
Interferer distances	**Distance from wanted cell 1.95 m**	**Distance from wanted cell 4.85m**	**Distance from wanted cell 7.75m**	**Distance from wanted cell 10.64m**	**Distance from wanted cell 13.54m**
1.45m	100.0	99.9	99.6	98.7	97.1
4.35m	100.0	99.9	99.5	98.2	96.0
7.25m	100.0	99.9	99.5	97.9	95.0
10.14m	100.0	100.0	99.5	97.7	94.2
13.04m	100.0	100.0	99.6	97.8	93.8

The average probability of call success from table D6 is 98.6 %.

We conclude that the frequency can be re-used every third house from the interferer.

Scenario 2: Interference across a street

For the purposes of this model, we define a simplified, relatively symmetrical house. The following assumptions are made about the house:-

Detached made of cavity brick
Facing a street 12m wide
Frontage 5m with a window width of half that.
Depth of house 8m

It is assumed that the loss through a cavity brick wall is 13dB. This was measured at right angles by Bradford University, although this study is not documented. It is assumed that that same value holds up to an angle which has not yet been determined.

The following assumptions are made for the radio system

Transmit power 0dBm from previous calculations
Height of transmitter and receiver averages 1.5m in order to find easy passage through windows.

Method

There is no existing standard to model interference between suburban houses, therefore certain assumptions were necessary.

The scenario assumed two parallel rows of terraced houses, separated by a street and that source transmitter in one house can create interference to a victim receiver in any house in the other row. Because the two rows of houses are parallel, the angle at which the interfering signal arrives at the victim house will be the same as its departure angle from the source house. It is therefore possible to separate the losses of the interfering signal leaving the source from the losses to the signal arriving at the victim house and subsequently add them for each angle.

The interference was assumed to be from a pico cell adjacent to a wall in the source house and calculations were made for three positions along that wall.

The interference victim was assumed to be a handset at ear level within a house in the other row. For convenience it was assumed to be on the centre line of the house and also at a range of distances into the house.

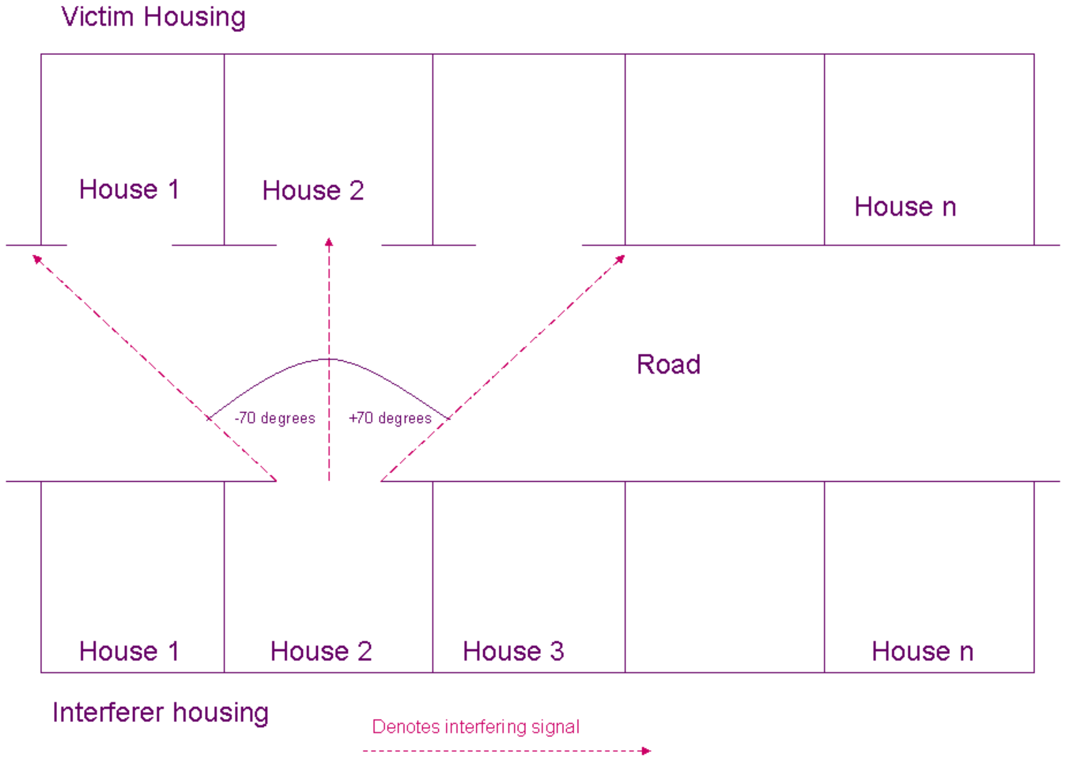
For both the source and victim house the losses were calculated for a range of angles (The calculated attenuation at each angle took the following into account:

absorption
reflection
refraction

The interference signal strengths were calculated from the path loss of the rays propagating across the street to the victim house, contained within an arc -70^o to +70^o. The loss was calculated from a range of positions in the victim house over this arc and the path which suffered least loss was selected.

This interference scenario is depicted in figure D.2.

Figure D.2 Interference mechanism across the street.



Losses across the street

For practical purposes the transmissions across the street will conform to free space path loss although there will be variations due to multipath effects.

Loss within the building

For transmission across the street the path loss should be based on free space. It is possible to calculate the loss inside the house relative to the free space path loss based on the information given in ITU-R P.1238. The path loss exponent used for free space is 20 whilst that specified for domestic interiors in ITU-R P.1238 is 28; therefore the loss relative to free space will be 8 Log *d*.

Calculating the loss in the two buildings

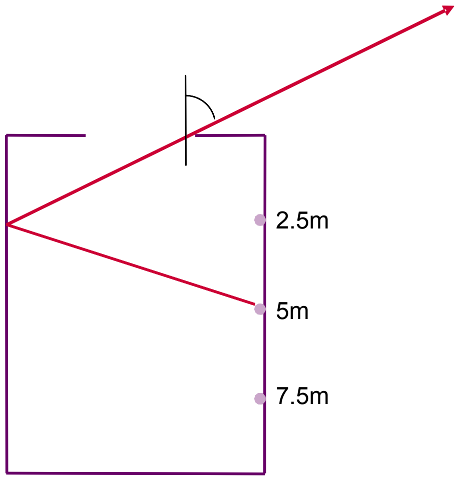
By selecting for each angle the least path loss from the methods available and adding the factor for the losses within the building it is possible to determine the path loss for each angle. The methods of transmission which have been considered are:-

- penetration through the structure
- reflection from the internal surfaces and out through the windows
- diffraction around the edges of the window

For a test point to one side inside a house, table D.11 combines the minimum loss to exit the building and marginal losses resulting from the clutter within the building as described under *Loss within the building*. It should be noted that where there is internal reflection this has had to be included on an as-occurs basis. Since we do not have a formula for ray tracing in a domestic residence we have worked from first principles where possible. Where calculations have become overly complex the ray tracing approach has not been used.

Reflection

Figure D.3 Process of reflection through window



Figures for reflection from a brick wall are not available in Recommendation ITU-R P.1238. It was noted that lightweight concrete and plasterboard had relatively similar characteristics. There are no figures for plasterboard at 1 GHz but it was noted that the figures for the higher frequencies barely changed with frequency. It was therefore decided that lightweight concrete would yield an adequate representation of a plastered wall made of building blocks or bricks. Table D.8 shows the reflection losses from a brick wall for a range of angles.

Table D.8 Reflection loss from brick wall

Angle	Reflection Loss (dB)
10°	7.35
20°	6.88
30°	6.18
40°	5.3
50°	4.32
60°	3.27
70°	2.19
80°	1.1

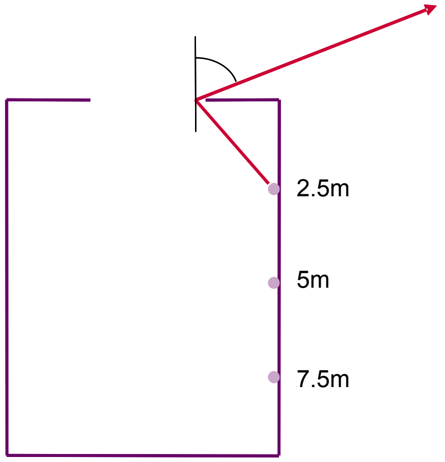
The angle in Table D.8 is between the incoming ray and the perpendicular to the wall.

It can be seen from these figures that the proportion of the radiation which penetrates into the wall falls dramatically after 50° and the wall attenuation figures for incident angles of more than 50° should be amended to reflect this. By 70° practically nothing is going into the wall.

The procedure used followed that defined in ITU-R P.1238.

Diffraction

Figure D.4 Process of diffraction through window.



Three test transmission points were set up inside the house, they are against the wall, where a transmitter might be located set back into the room by:-

2.5m
5.0m
7.5m

Table D.9 is a diffraction table for these test points based on ITU-R P.526-5.

In this table the angles are based on the line from the front of the house perpendicular to the street being 0°. The negative angles are towards the same side of the house as the transmitter. Since the window is assumed to be in the middle of the wall the direction of best transmission would be expected to be biased towards the positive angles.

Table D.9 Diffraction losses from test transmission points inside house

	Diffraction loss, dB		
Angle	**test point at 2.5m from front of house**	**test point at 5.0m from front of house**	**test point at 7.6m from front of house**
-70°	Result not available	31.1	32.9
-60°	28.3	30.8	32.5
-50°	28	30.1	31.7
-40°	27.3	28.9	30.3
-30°	26.2	27.2	28.4
-20°	24.8	25	23.5
-10°	22.8	21.7	21.5
0°	20.3	16.5	13.6
10°	16.65	7.2	0
20°	10.8	0	0
30°	0	0	9.8
40°	0	16.4	18.4
50°	0	21.4	23.3
60°	9.9	24.8	26.5
70°	18.1	26.6	29
80°	22.1	28.9	30.7

For the case against the front wall angles less than ±50° are assumed to result in13dB loss through the wall. From 50° to 70° a loss of 16dB through the wall is assumed. Angles of more than 70° should be assumed to result in internal reflection and no outward transmission.

A diffraction table was also generated which represented a receiver at the same distances but in the centre of the room. Angles in this case will be symmetrical.

Table D.10. Diffraction losses at test receiver points inside house

	Diffraction loss, dB		
Angle	**test point at 2.5m from front of house**	**test point at 5.0m from front of house**	**test point at 7.5m from front of house**
80°	26	29.9	31.4
70°	24.4	28.8	30.9
60°	22.1	27	29.2
50°	18.6	24.6	26.9
40°	13.1	21	23.8
30°	4.75	15.6	19.3
20°	0	6.3	11.4
10°	0	0	0.03
0°	0	0	0

The front wall case for the middle of the room will represent a user standing in the window. It should be assumed that all angles between ±70° will be 0dB.

The procedure for calculating diffraction losses followed the method defined in Recommendation ITU-R P.526.

Table D.11 Combination of the minimum loss to exit the building and marginal losses resulting from the clutter within the building

	Path loss, dB			
Angle	**test point 0m from front of house**	**test point 2.5m from front of house**	**test point 5m from front of house**	**test point 7.5m from front of house**
-70°	16	12.5	13	13
-60°	16	13	13	13
-50°	13	13	13	13
-40°	13	16	16	11.8
-30°	13	16	16	16
-20°	13	28	30.6	30.5
-10°	13	26	27.2	28.5
0°	13	13	18.6	20
10°	13	13	13	7
20°	13	13	5.6	7
30°	13	3.2	5.6	16.8
40°	13	3.2	18.6	20
50°	13	3.2	18.6	20
60°	16	13.1	18.6	20
70°	16	18.6	18.6	20
80°	30	18.6	18.6	30

Table D.12 follows the same approach as D.11 for a test point in the centre of the house

Table D.12 Combination of the minimum loss to exit the building and marginal losses resulting from the clutter within the building

	Path loss, dB			
Angle	**test point 0m from front of house**	**test point 2.5m from front of house**	**test point 5.0m from front of house**	**test point 7.5m from front of house**
80°	20	16.2	18.6	20
70°	6	16.2	18.6	20
60°	0	16.2	11.8	20
50°	0	16.2	18.6	20
40°	0	16.2	18.6	11.32
30°	0	7.79	18.6	20
20°	0	3.2	11.9	18.4
10°	0	3.2	5.6	7.03
0°	0	3.2	5.6	7

Path loss across the street

The path loss across the street is dependent on the distance covered and since the distance is proportional to the reciprocal of the cosine of the angle at which it crosses it is possible to include this factor into the angle calculations and so that the path loss varies solely with the width of the street. The required factor is 20 log (1/cos(angle)). Thus:-

Table D13: Additional path loss at victim building at each arc angle

Angle	Path loss, dB
80°	15.2
70°	9.32
60°	6.02
50°	3.84
40°	2.31
30°	1.24
20°	0.54
10°	0.13

Finding the results for any angle

It is possible to combine the results for a transmitter at the side of the house and a receiver at the opposite side and the impact of the angle across the street by combining the results for each angle. Also since the side of the house on which the transmitter is placed cannot be determined the positive and negative angles can also be combined. In this case a mean loss and standard deviation was generated. This method is not adequate to represent the physical model defined but will provide a better representation of reality which has more variables than the model.

The results appear in Table D.14

Table D.14 Mean path loss from interferer at victim building at each arc angle

Angle	Mean path loss, dB	Mean path loss corrected for angle, dB	standard deviation
80°	40.55	55.75	5.18
70°	30.39	39.71	7.78
60°	29.47	35.49	8.8
50°	27.4	31.24	9.5
40°	24.47	26.78	8.8
30°	24.4	25.64	9.7
20°	25.08	25.62	12.9
10°	21.54	21.67	8.31
0°	20.1	20.23	4.25

The high standard deviation at 20° indicates that the maximum risk of interference is line of sight effects through windows coupled with low losses.

For the purpose of calculating interference into houses opposite the calculation should be based on 20.1dB of loss. A standard deviation of approximately 8.5 will represent a general case. This will permit the additional protection which results from a slight offset to one side or the other to be easily derived from the first set of figures. The high standard deviation at 20° demonstrates that the offset use in further calculations must be greater than 20°, i.e. at least 30°.

Loss across the street

If the width of the street is assumed to be 12m and the mean position in each house is assumed to be 2.5m then the loss will be free space for 17m plus the mean corrected loss:-

Free space for 17m = 62.5dB
Additional loss = 20.1dB
Mean loss across street = 82.6dB

A fast fading margin must be subtracted from this figure to correct for the effects of multipath, a value of 6dB has been assumed. This margin corrects for the effects of multipath on the difference between the wanted and the interfering signal.

Mean loss across the street = 76.6dB

Victim cell in suburban house

Size of House: 5m by 8m, 2 floors

Maximum horizontal distance = 9.4m

The figures should be separately calculated for the ground floor and the first floor because the floor loss in ITU-R P.1238 for a single floor is 4dB.

The house is immediately opposite.

In this case the standard deviation is the sum of the squares of 8dB (in house ITU-R P.1238 across street (8.5 derived above), standard deviation = 11.7

It is assumed that both the interferer and the victim have the same power.

The distance from the victim to the transmitter in the victim's house is divided into 5 distances and the carrier to interference ratio at a mean point of each distance is calculated. Subtracting 9dB gives a value for the margin above minimum carrier to interference ratio for GSM. Call success probability is then calculated for each point, and these values are used to produce a mean call success probability. Tables D.15 and D.16 give the results for the ground floor and the first floor.

Table D.15. Call success on residential ground floor for opposite house

Distance of user from own pico cell	Mean distance, m	Path loss of wanted signal, dB	C/I	C/I-9	C/I-9 as standard deviations	Probability of call success
8 to 10m	9	64.11	12.5	3.5	0.3	61.2%
6 to 8m	7	61.06	15.5	6.5	0.555	69.2%
4 to 6m	5	56.97	19.6	10.6	0.91	81.6%
2 to 4m	3	50.76	25.8	16.8	1.44	91.9%
0 to 2m	1	37.4	29.2	20.2	1.73	95.5%
					Mean	**79.9%**

Table D16 Call success on residential first floor for opposite house

Distance of user from own pico cell	Mean distance, m	Path loss of wanted signal, dB	C/I	C/I-9	C/I-9 as standard deviations	Probability of call success
8 to 10m	9.41	64.7	7.9	-1.1	-0.09	50.0%
6 to 8m	7.52	61.9	10.7	1.7	0.145	54.0%
4 to 6m	5.71	58.6	14.0	5.0	0.427	65.5%
2 to 4m	4.07	54.5	18.1	9.1	0.78	75.8%
0 to 2m	2.93	50.5	22.1	13.1	1.12	85.4%
					Mean	**66.1%**

The critical case is evidently the first floor:-

If the location is 30° away from the front of the house is used then 5.5dB additional path loss is gained. This results in the call success probability in Table D.17

Table D.17. Call success on residential first floor at house with 30° separation

Distance of user from own pico cell	Mean distance, m	Path loss of wanted signal, dB	C/I	C/I-9	C/I-9 as standard deviations	Probability of call success
8 to 10m	9.41	64.7	13.4	4.4	0.376	61.8%
6 to 8m	7.52	61.9	16.2	7.2	0.615	72.6%
4 to 6m	5.71	58.6	19.5	10.5	0.897	78.8%
2 to 4m	4.07	54.5	23.6	14.6	1.25	88.5%
0 to 2m	2.93	50.5	27.6	18.6	1.59	93.3%
					Mean	**79.0%**

A 30 degree span at the width of the street is a 12m span or 3 houses. It should also be noted that the house may have more than 2 floors.

Table D.18 provides results for a location 50° away from the front of the house.

Table D.18 Call success on residential first floor at house with 50° separation

Distance of user from own pico cell	Mean distance, m	Path loss of wanted signal, dB	C/I	C/I-9	C/I-9 as standard deviations	Probability of call success
8 to 10m	9.41	64.7	19	10	0.855	78.8%
6 to 8m	7.52	61.9	21.8	12.8	1.09	84.1%
4 to 6m	5.71	58.6	25.1	16.1	1.38	90.3%
2 to 4m	4.07	54.5	29.2	20.2	1.73	95.5%
0 to 2m	2.93	50.5	33.2	24.2	2.07	97.7%
					Mean	**89.3%**

50° each side of the house subtends 28.6m which represents approximately six houses. This represents six frequencies on one side of the road, six on the other side and six behind the row of houses, i.e. 3 channels more than the maximum 15 channels available. We therefore conclude that coordination will be required and that it will only be possible to assign frequencies from a total of 15 at random if the usage percentages are relatively low.

Annex E

Office scenario calculations for cdma2000 1X

The aim of these calculations is to determine the necessary separation distance to protect a low power GSM system in adjacent building from a low power cdma2000 1x system.

A generic scenario has been modelled to assess the potential of co-channel interference from a low power cdma2000 1x system and the likelihood of call success of a low power GSM system in an adjacent building. A system designer may in practice do more precise modelling taking into account of the specific layout and the furniture inside the particular building requiring the service.

Modelling the necessary separation distance to avoid interference between low power GSM systems in adjacent buildings

The main challenge for this problem is the variability of the received signal around the inside of the building and between buildings. A signal is assumed to suffer interference when the ratio of wanted signal to interfering signal is less than the minimum carrier-to-interference (C/I) ratio specified for the system. If both sources of variability can be assumed to be Gaussian, it is possible to take the standard deviations from both the wanted and interfering path and to apply this to obtain the margin above minimum C/I and the probability of call success. It is unlikely that the distributions would be truly Gaussian but they are likely to be close enough to Gaussian for the method to provide representative results.

System characteristics

Calculations were based on GSM pico cell and cdma2000 1x deployments in office buildings. The pico cell base station characteristics used in the calculations were

System: GSM
Frequency: 1880 MHz
Bandwidth: 200kHz
Power: 23dBm per 200kHz carrier
Antenna gain: 0dBi
Cell service radius: 40m and 50m

System: cdma2000 1x
Frequency: 1880 MHz
Bandwidth: 1.228MHz
Raster size: 1.25MHz
Power: 23dBm per 1.228MHz
Antenna gain: 0dBi
Cell service radius: 40m and 50m

The building width was set at 50m.

The equivalent interfering transmit power of a 23dBm cdma2000 1x pico cell in a 200 kHz GSM carrier is calculated by:

$$23\text{dBm} - \log\left(\frac{1.228}{0.2}\right) = 15.1\text{dBm per 200kHz}$$

Within the DECT guard band 1876.7-1880MHz, assuming 200kHz is used as a guard band to protect adjacent high power GSM services, there are enough frequencies for 15 low power GSM carriers or 2 low power cdma2000 1x carriers.

Figure E.1. Transmitted power per 200kHz for each potential cdma2000 1x carrier based on its emission mask

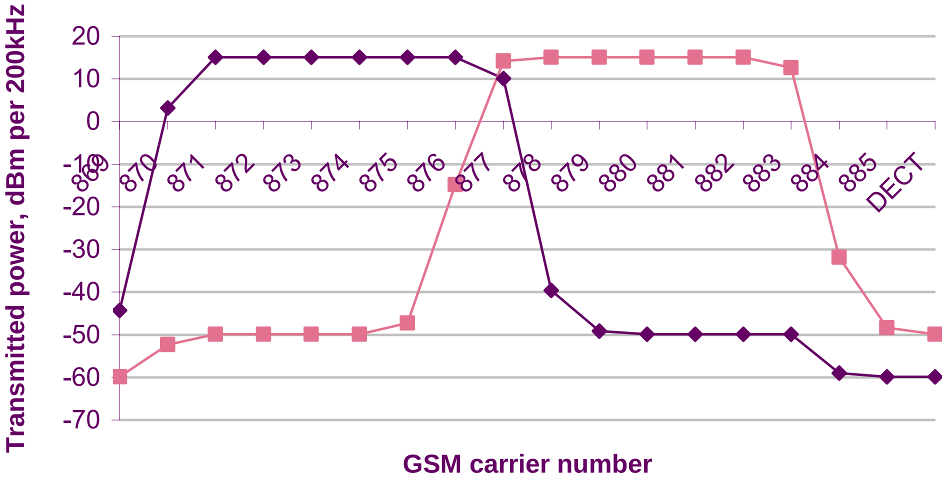


Figure E.1 shows the transmitted power from each potential cdma2000 1x carrier into each potential 200kHz GSM carrier. Assuming one carrier is used as a guard band to protect the adjacent high power GSM services, the first potential low power, base transmit, GSM frequency is 1877MHz represented by carrier number 871.

Propagation model

Within the building the field strength will be reduced by diffraction, where the first Fresnel zone is obstructed (due to building layout and office furniture). Recommendation ITU-R P.1238-3 provides the following equation to calculate the propagation losses within buildings:

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_{floor}(n) - 28 \quad \text{dB}$$

where:

L_{total} :	total propagation loss
N :	distance power loss coefficient
f :	frequency (MHz)
d :	separation distance (m) between the base station and portable terminal (where $d \geq 1$m)
L_{floor} :	floor penetration loss factor (dB)
n :	number of floors between base station and portable terminal ($n \geq 1$).

Recommendation ITU-R P.1238-3 indicates that the typical value for *N* within an office building is 30 (losses within a building due to floor penetration are not considered).

Additional losses of wall partitions are to be included. This study assumed a loss of 4dB per wall, spaced every 10m. This loss value is taken from COST 231.

The in-building propagation loss equation becomes:

$$L = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 \qquad \text{dB}$$

where

d : separation distance (m) between the base station and portable terminal (where $d \geq 1$m)

Calculating wanted signal from the serving GSM pico cell in own building

The aim of these calculations is to determine the necessary separation distance to protect a low power GSM system in adjacent building from a low power cdma2000 1x system using the same centre frequency. These results also hold true for any GSM carrier within the 1.228MHz cdma2000 1x carrier bandwidth.

A single pico cell with a serving radius of 50m is considered. For the purposes of this calculation the coverage is broken into concentric rings at 10m, 20m, 30m, 40m or 50m from the transmitter. The user is placed at the mid-point between each ring and the signal level is calculated. This is illustrated in Figure E.2 where the user in the 10 – 20m ring a distance of 15m is used in the propagation calculations.

Figure E.2. Distance of user from wanted transmitter

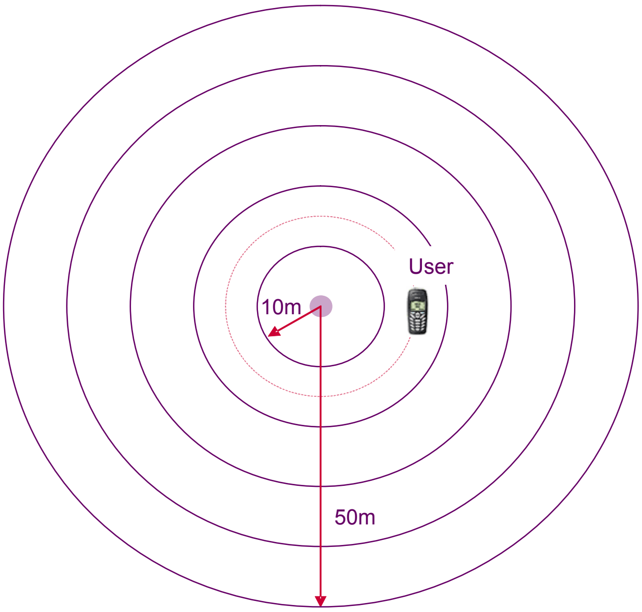


Table E.1 gives the calculated interference levels that can be tolerated based on a 23dBm pico cell base station based on above propagation loss equation.

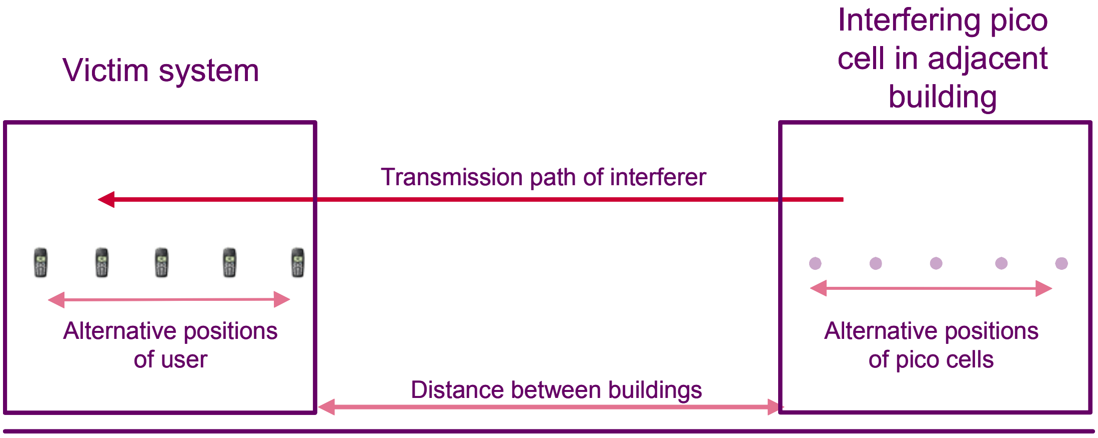
Table E.1: Received signal levels from a 23dBm pico cell base station

Distance from pico cell, m	Path loss in building, dB	Received signal by user, dBm	C/I protection needed, dB	Maximum permitted interference, dBm
0 - 10	71.5	-37.5	9	-46.5
10 - 20	84.5	-55.8	9	-64.8
20 - 30	93.8	-66.4	9	-75.4
30 - 40	101.5	-74.8	9	-83.8
40 - 50	108.5	-82.1	9	-91.1

Interference from the cdma2000 1x pico cell in an adjacent building

To model the interference into the receiver we consider a pico cell in an adjacent building which has a serving radius of 50m. The interfering signal exits from an adjacent building through the window, crosses the intervening space, then enters through another window to reach the user’s terminal. Figure E.3 illustrates the path of the interfering signal.

Figure E.3. Interfering signal path



The field strength within the victim building from the interferer cannot directly be calculated by the in-building equations because the interfering signal has already passed through a space (between the buildings) without in-building loss before entering the victim building. This problem can be addressed by calculating the path losses relative to free space path loss to find the path loss due only to the building conditions. These figures are added to the free space path loss for the total distance in order to obtain the combined loss for a range of separation distances.

The losses for each part of this path are:

$$L_{FreeSpace} = 20 \log_{10} f + 20 \log_{10} d - 28$$

$$L_{Inbuilding} = 20 \log_{10} f + 30 \log_{10} d + 0.4d - 28 + 4$$

$$L_{BuildingOnly} = L_{Inbuilding} - L_{FreeSpace} = 10 \log_{10} d + 0.4d + 4$$

$L_{Inbuilding}$ has an additional loss of 4dB caused by the interfering signal exiting or entering each building via the windows.

The pico cell and user can be positioned anywhere within the building, varying the potential total length of the interfering path and the likely received interfering signal. Tables E.2 and E.3 show the in-building penetration loss for various positions of interferer and victim receiver. Table E.4 shows the potential combinations of total penetration losses in both buildings.

Figure E.4. Breakdown of the calculation of the transmission path of interferer

Table E.2: Penetration in adjacent building

Distance of transmitter from window in adjacent building, m	Penetration loss, dB ($L_{BuildingOnly}$)
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

Table E.3: Penetration in victim building

Distance of user from window in victim building, m	Penetration loss, dB ($L_{BuildingOnly}$)
0 - 10	13.0
10 - 20	21.8
20 - 30	28.0
30 - 40	33.4
40 - 50	38.5

Table E.4: Matrix of the potential total penetration losses of the interfering signal in the victim and adjacent building, dB (derived by calculating the possible combinations of total penetration loss from table E.2 and table E.3).

Distance of user from window in victim building, m	**Penetration loss, dB**				
	Distance of transmitter from window in adjacent building				
	0 - 10m	**10 - 20m**	**20 - 30m**	**30 - 40m**	**40 - 50m**
0 - 10	26.0	34.8	41.0	46.4	51.5
10 - 20	34.8	43.5	49.7	55.2	60.3
20 - 30	41.0	49.7	56.0	61.4	66.5
30 - 40	46.4	55.2	61.4	66.9	72.0
40 - 50	51.5	60.3	66.5	72.0	77.1

The mean penetration loss due to positional variation, $\overline{X}$ = 53.88dB

The sample standard deviation of data in a sample is calculated by:

$$\text{Standard deviation} = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}(X_i - \overline{X})^2}$$

The standard deviation calculated is 12.90dB. This represents the variation of penetration loss due to different placements of the interfering transmitter and the victim user terminal.

There are additional variations to consider due to shadowing, when modelling the variation in the received signals, these are assumed to be:

- 10dB from the wanted transmitter to the user, from Recommendation ITU-R P.1238-3.
- 7.7dB from the interfering signal. (The interfering path has shadow fading within the building, but no shadow fading is appropriate for the part of the path which passes between the buildings. Therefore the standard deviation of the total path is a smaller figure than the standard deviation quoted in P.1238-3 for in-building only.)

The total standard deviation for the entire path is

$$\sqrt{7.7^2 + 10^2 + 12.90^2} = 18.04$$

The interfering signal received by the user is calculated from:

EIRP – total losses + fast fade margin = interfering signal level

The fast fade margin results from the multipath in the building. The path loss model is optimised to show the usable power corrected for the effects of fast fade. Therefore the interference requires a margin relative to the figure shown by the path loss model which corrects for the percentage of the time during which the effects of multipath are maximised.

Table E.5: Mean interfering signal level in victim building from 23dBm outdoor pico cell

Total distance between user and interfering cell, m	Mean EIRP in 200kHz bandwidth, dBm	Free space path loss, dB	Mean in-building penetration loss, dB	Fast Fade margin, dB	Interfering signal level, dBm
50	15.1	71.5	53.88	6	-104.2
100	15.1	77.5	53.88	6	-110.2
150	15.1	81.0	53.88	6	-113.8
200	15.1	83.5	53.88	6	-116.3
250	15.1	85.4	53.88	6	-118.2
300	15.1	87.0	53.88	6	-119.8
350	15.1	88.4	53.88	6	-121.1
400	15.1	89.5	53.88	6	-122.3
500	15.1	91.5	53.88	6	-124.2
600	15.1	93.0	53.88	6	-125.8
700	15.1	94.4	53.88	6	-127.1

Calculating the likelihood of call success

It is possible to obtain the interference for the entire victim cell by slicing the cell into 10m rings and estimating the percentage interference for each of these rings using standard statistical methods.

Table E.6: Difference between signal to be protected and mean interfering signal

	Margin above minimum C/I, dB										
Distance of user from own pico cell, m	Distance of the interfering transmitter from the victim user										
	50m	100m	150m	200m	250m	300m	350m	400m	500m	600m	700m
0 - 10	57.77	63.79	67.31	69.81	71.75	73.33	74.67	75.83	77.77	79.36	80.69
10 - 20	39.46	45.48	49.00	51.50	53.44	55.02	56.36	57.52	59.46	61.04	62.38
20 - 30	28.80	34.82	38.34	40.84	42.78	44.37	45.70	46.86	48.80	50.39	51.72
30 - 40	20.42	26.44	29.96	32.46	34.40	35.98	37.32	38.48	40.42	42.00	43.34
40 - 50	13.14	19.16	22.69	25.19	27.12	28.71	30.05	31.21	33.14	34.73	36.07

The standardised normal variable is the difference between the mean interfering signal and signal to be protected expressed as a number of standard deviations. The table below is an interim step, where the standardised normal variable, Z, has been found in order to calculate the probability of a successful call using a Gaussian distribution table, see table E.8.

Table E.7: Standardised normal variable, Z

	Standardised normal variable										
	Distance of the interfering transmitter from the victim user										
Distance of user from own pico cell, m	**50m**	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0 - 10	3.20	3.54	3.73	3.87	3.98	4.06	4.14	4.20	4.31	4.40	4.47
10 - 20	2.19	2.52	2.72	2.85	2.96	3.05	3.12	3.19	3.30	3.38	3.46
20 - 30	1.60	1.93	2.13	2.26	2.37	2.46	2.53	2.60	2.70	2.79	2.87
30 - 40	1.13	1.47	1.66	1.80	1.91	1.99	2.07	2.13	2.24	2.33	2.40
40 - 50	0.73	1.06	1.26	1.40	1.50	1.59	1.67	1.73	1.84	1.92	2.00

(standard deviation=18.04)

Table E.8 shows the probability of a successful call if the user is within the 10m, 20m, 30m, 40m or 50m ring from the wanted pico cell for various distances of the path length of the interferer.

Table E.8: Probability of successful call

	Probability of successful call										
	Distance of the interfering transmitter from the victim user										
Distance of user from own pico cell, m	**50m**	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0 - 10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 - 20	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20 - 30	0.94	0.97	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
30 - 40	0.87	0.93	0.95	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99
40 - 50	0.77	0.86	0.90	0.92	0.93	0.94	0.95	0.96	0.97	0.97	0.98

Assuming an even distribution of users within the cell, the following figures (Table E.9) can be derived for users at particular distances from the cell.

Table E.9: Distribution of users within cell

Distance from pico cell, m	Area of ring, m^2	Proportion of users within the ring
0 - 10	314.2	0.04
10 - 20	942.5	0.12
20 - 30	1570.8	0.20
30 - 40	2199.1	0.28
40 - 50	2827.4	0.36

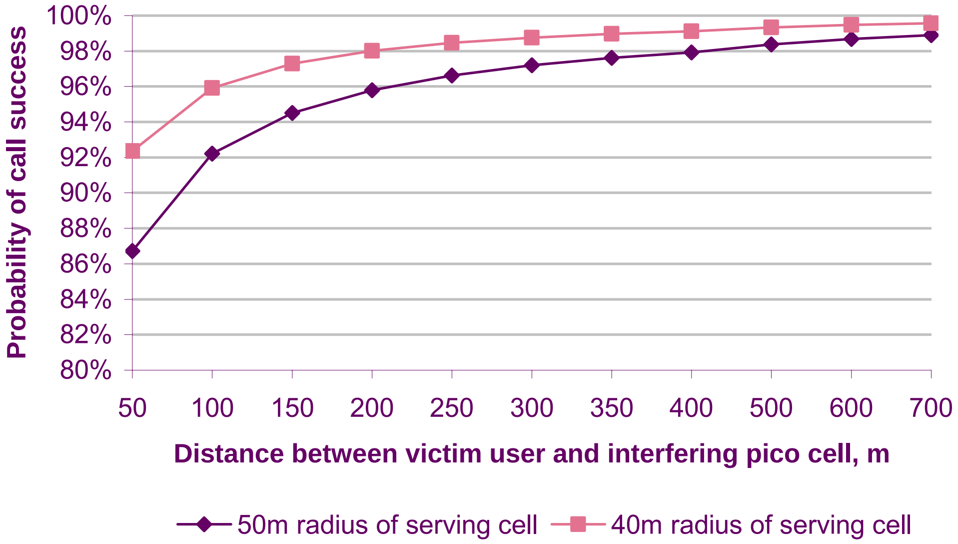
Table E.10 shows the total probability of a successful call and is derived by taking the probability of a successful call multiplying by the proportion of users. These values are added together to find the total probability of a call success.

Table E.10: Total probability of call success for a 50m serving pico cell

	Proportion of successful calls										
Distance of user from own pico cell, m	**Distance of the interfering transmitter from the victim user**										
	50m	**100m**	**150m**	**200m**	**250m**	**300m**	**350m**	**400m**	**500m**	**600m**	**700m**
0-10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
10-20	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
20-30	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
30-40	0.24	0.26	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.28
40-50	0.28	0.31	0.32	0.33	0.34	0.34	0.34	0.34	0.35	0.35	0.35
Total probability	0.867	0.922	0.945	0.958	0.966	0.972	0.976	0.979	0.984	0.987	0.989

Figure E.5 shows the call success probability for a 50m cell from Table E.10. For comparison the probability for a 40m cell serving radius was calculated and is also shown.

Figure E.5. Probability of call success for 23dBm base stations in offices

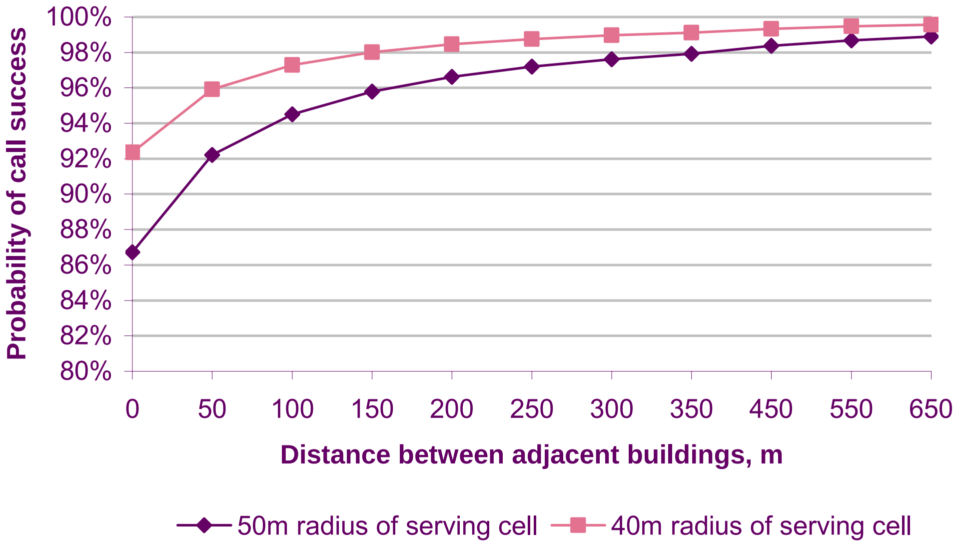


The aim of these calculations is to determine the necessary separation distance to protect a low power GSM system in adjacent building from a low power cdma2000 1x system using the same centre frequency. These results also hold true for any GSM carrier within the 1.228MHz cdma2000 1x carrier bandwidth.

To achieve a 97% probability of a successful call, the separation distance between the user and the interfering transmitter has to be 300m for a 50m radius serving cell and 150m for a 40m serving cell.

If you take an average distance of 25m for the user and the interfering transmitter to the window, this is equivalent to 50m for the total indoor path of the interfering signal. Then the distance between the adjacent buildings can be assumed to be the value in the x-axis of Figure E.5 minus 50m. So assuming a 50m radius serving cell and a distance between adjacent buildings of 250m, the probability of a call success is 97%. This is demonstrated in Figure E.6.

Figure E.6. Probability of call success for 23dBm base stations in offices



It may be possible to use the dimensions of the building to achieve some of the required separation to mitigate against interference. This requires coordination at the planning stage when designing the positions of pico cells to achieve a 97% call success rate.