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Technical Report

Fixed Radio systems;
Multipoint equipment;
Report on Fixed Wireless Access systems which apply Mesh topology and operate in applicable Fixed Service bands within the 3 GHz to 11 GHz range

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Contents

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Transmission and Multiplexing (TM).

In the present document on Mesh systems below 11 GHz coexistence calculations between P-MP and Mesh-systems are presented. Co-channel adjacent area cases and adjacent frequency block same area cases are studied. SEAMCAT simulation tool has been used where applicable. Coexistence calculations for mesh system with directive antennas has been added. System parameter consistency within the report has been checked as well as consistency with CEPT/ECC Report 33 [7].

1 Scope

The present document provides information about systems with mesh network topology to evaluate:

- special features of mesh-network such as network architecture, system deployment, network evolution, geographical coverage, link distances, role of traffic control, power control, antennas;
- transmission capacity, spectrum use, spectral efficiency, RF-channelling, use of adaptive modulation and coding;
- co-existence with other access systems using the same frequency band.

Focus of this report is on 3,4 GHz band for mesh-systems using omni-directional antennas. For mesh-systems using directional antennas calculations also some calculations for 10,5 GHz band are presented.

2 References

For the purposes of this Technical Report (TR), the following references apply:

[1] ETSI EN 301 021: Time Division Multiple Access (TDMA); "Fixed Radio Systems; Point-to-multipoint equipment; Time Division Multiple Access (TDMA); Point-to-multipoint digital radio systems in frequency bands in the range 3 GHz to 11 GHz".

[2] ETSI EN 302 085: "Fixed Radio Systems; Point-to-Multipoint Antennas; Antennas for point-to-multipoint fixed radio systems in the 3 GHz to 11 GHz band".

[3] ETSI TR 101 939: "Fixed Radio Systems; Multipoint-to-Multipoint systems; Requirements for broadband multipoint-to-multipoint radio systems operating in the 24, 25 GHz to 29,5 GHz band and in the available bands within the 31,0 GHz to 33,4 GHz frequency range".

[4] ETSI TR 101 904: "Transmission and Multiplexing (TM); Time Division Duplex (TDD) in Point-to-Multipoint (P-MP) Fixed Wireless Access (FWA) systems; Characteristics and network applications".

[5] ETSI TR 101 856: "Broadband Radio Access Networks (BRAN); Functional Requirements for Fixed Wireless Access systems below 11 GHz: HIPERMAN".

[6] ETSI TR 101 079: "Network Aspects (NA); Routeing of calls to pan-European services using European Telephony Numbering Space (ETNS)".

[7] CEPT/ECC/Report 33: "The analysis of the coexistence of FWA cells in the 3,4 to 3,8 GHz bands".

[8] IEEE 802.11a: "Wireless LAN Medium Access Control (MAC) an Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5 GHz band".

[9] CEPT/ERC Recommendation 14-03: "Harmonized radio frequency channel arrangements and block allocations for low and medium capacity systems in the band 3400 MHz to 3600 MHz".

[10] CEPT/ERC Recommendation 12-08: "Harmonized radio frequency channel arrangements and block allocations for low, medium and high capacity systems in the band 3600 MHz to 4200 MHz".

[11] CEPT/ERC Recommendation 12-05: "Harmonized radio frequency channel arrangements for digital terrestrial fixed systems operating in the band 10,0-10,68 GHz".

[12] Richard van Nee, Ramjee Prasad: "OFDM for the Wireless Multimedia Communications", Artech House Publishers.

[13] IEEE 802.16a: "Air Interface for Fixed Broadband Wireless Access Systems - amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2 to 11 GHz".

[14] IEEE 802.16.2-REVa: "Coexistence of Fixed Broadband Wireless Access Systems".

[15] The ACTS Project AC215 CRABS "Cellular Radio Access for Broadband Sevices"; Project report D3P1B: "Propagation Planning Procedures for LMDS". .

[16] ETSI EN 301 080: "Fixed Radio Systems; Point-to-multipoint equipment; Frequency Division Multiple Access (FDMA); Point-to-multipoint digital radio systems in frequency bands in the range 3 GHz to 11 GHz".

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

access point: network device with direct access to the core network

backhaul link: connection from mesh access point to core network interface

extended neighbourhood: joint set of neighbourhoods of each mesh device in the neighbourhood of a mesh device

Fixed Wireless Access (FWA): wireless access application in which subscriber stations are fixed in location during operation, which includes nomadic operation

local access: is used in the telecommunications sense: short range (< 100 m) wireless access to other, possibly wired, networks

max mean EIRP: refers here to the EIRP averaged over the transmission burst at the highest power control setting

Mesh Access Point: mesh device with access to backhaul infrastructure

Mesh Access Point site: can locate one or more Mesh Access Points

mesh cluster: area and nodes covered by one Mesh Access Point

mesh: multipoint to multipoint topology (MP-MP)

neighbourhood: set of mesh devices consisting of a mesh device and all mesh devices with which this device has direct links

node: system in a mesh network

remote access: used in the telecommunications sense: long range (< 10 km) wireless access to other, possibly wired, networks

NOTE: Remote access networks are also referred to as "local loop networks".

repeater: device consisting of at most a pair of systems, which solely consists for the purpose of retransmitting the received information

sector: APT in conjunction with an antenna with a 3 dB beamwidth less than 360°

subscriber: means one connected via mesh-network

3.2 Symbols

For the purposes of the present document, the following symbols apply:

dB	deciBel
dBm	deciBel relative to 1 mW
GHz	Giga Hertz
kbit/s	kilobit per second
ms	millisecond
ns	nanosecond
Mbit/s	Megabit per second
MHz	Mega Hertz

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AP	Access Point, central hub in a P-MP network
ATPC	Automatic Transmit Power Control
BER	Bit Error Ratio
BPSK	Binary Phase Shift Keving
BRAN	Broadband Radio Access Networks
BS	Base Station, central hub in a point-to-multipoint network
CEPT	European Post and Telecommunications Consultative Committee
C/I	Carrier to Interference
CS	Central Station (e.g of P-MP system)
EIRP	Equivalent Isotropic Radiated Power
FDD	Frequency Division Duplex
FS	Fixed Service
FWA	Fixed Wireless Access
HIPERMAN	High Performance Radio Metropolitan Access Networks (for frequency bands below 11 GHz)
IP	Internet Protocol
ISOP	Interference Scenario Occurrence Probability
ITU	International Telecommunications Union
LAN	Local Area Network
LOS	Line Of Sight
MAP	Mesh Access Point
MP-MP	Multipoint-to-Multipoint (Mesh)
NFD	Net Filter Discrimination
OFDM	Orthogonal Frequency Division Multiplexing
P-MP	Point-to-MultiPoint
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SEAMCAT	Spectrum Engineering Advanced Monte Carlo Analysis Tool
SS	Subscriber Station
TDD	Time Division Duplex
TS	Terminal Station (e.g in P-MP system)

4 System description

4.1 General

Mesh (MP-MP) networks differ significantly from P-MP because all the terminals are similar and in equal position in the network and transmissions may take place between any two stations. The only exception is the terminal which forms the access point to the backbone network and could in some implementations control the scheduling of data transmissions within the network. The key mesh network variants can be differentiated by antenna system characteristics. Generally subscriber nodes in different variants are individual installations typically equipped with either omni-directional antennas or directional antennas. For convenience these variants are labelled as either "omni-directional" or "directional" mesh networks.

The mesh network form is more random than typical P-MP networks and may consist of either one or more mesh-clusters based on a relatively fixed frequency re-use plan in omni-directional networks or a more random frequency usage and antenna pointing characteristic in directional networks. In this report the special characteristics of mesh-network operating at FS-bands below about 11 GHz are described.

The ETSI BRAN project has published a report on functional requirements for FWA systems below 11 GHz known as HIPERMAN. Two network topologies are defined: Point-to-MultiPoint (P-MP) as mandatory and Mesh systems using omni-directional subscriber antennas as optional. A more detailed technical description of all access network topologies is presented in ref TR 101 856 [5] as well as technical justifications for RF-spectrum usage. A more detailed description of Mesh networks using substantially directional antennas is presented in ref TR 101 939 [3] for higher frequency bands. CEPT has issued a report of FWA coexistence at 3,5 GHz. Recognizing that coexistence of MP-MP mesh-systems in this band still requires to be addressed in future editions.

4.2 Mesh system description

4.2.1 Mesh system (MP-MP) network topology

All mesh-network variants consist of a cluster of stations each of which can have radio connection to one or more other stations. All stations, called here as nodes, may act as repeaters with local access for packet data traffic. Most of these stations can be located at customer premises. Traffic is routed via one or more nodes (typically not more than 3) to a node which is associated to the core network access point. Traffic within a mesh cluster does not have to be routed via the core network access point if a more beneficial route exist (subject to routing parameters. If there is nothing to send the transmitter of a node can be silent just listening to its neighbourhood for incoming bursts (see figure 1).

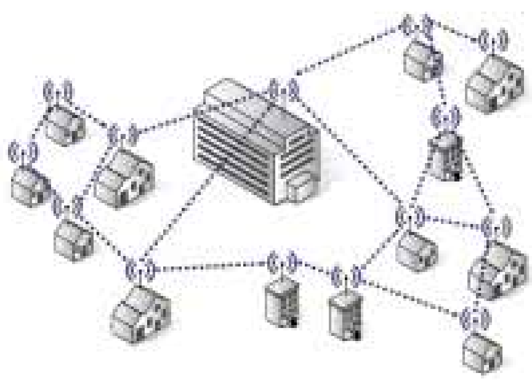


Figure 1: Mesh network example (any of the nodes may act as the access point)

4.2.2 Antennas

4.2.2.1 Omni-Directional Mesh

Omni-directional mesh antennas can exhibit relatively high gain because of vertical beam reduction. At mesh access points omni-directional antennas are typically also used but it is alternatively possible to use a few co-located equipments with sector antennas in order to aggregate more traffic into a single point.

Omnidirectional antennas allow simple and economical network evolution without the need for antenna directing when a new node is added.

Besides omnidirectional and sector antennas there is the possibility to use groups of directional antennas to get better control to interferences and to increase system gain.

More sophisticated antennas with steerable beams and/or switchable omni/directional modes are being developed to combine the benefits of all these antenna types. TDD offers the possibility to apply different antenna mode during transmit and receive period and e.g. EIRP-levels may be lowered to reduce interference spreading without sacrificing the system gain.

4.2.2.2 Directional Mesh

Directional mesh networks deploy antennas displaying moderate directivity similar to terminal stations in P-MP networks. When narrow-beam directional antennas are used, it is necessary to point them accurately and to be able to re-point in new directions as the network evolves to accommodate more subscribers. It is not practical to do this manually, so a remotely controlled pointing mechanism of some kind is required. There are three main ways to achieve this:

- by switching between a series of fixed antennas;
- by electro-mechanical steering of directional antennas;
- by electronically steered arrays.

A suitable choice of antenna radiation pattern and gain combined with relatively short link lengths allows the interference to be localized. Apart from the reduction in normal transmitter power, less margin (or less ATPC range) is required to overcome fading. Frequencies can then be re-used many times within a network, leading to significant gains in spectral efficiency. Since there are usually several choices for the structure of a mesh joining a given set of user stations, the actual link directions can be chosen to maximize re-use and thus further improve spectrum efficiency.

4.2.3 Traffic configuration

In any mesh network every node is able to bypass traffic to nearby nodes. Thus once a node is able to connect to any other node in the network, it automatically has access also to Mesh Access Point (MAP) over one or more radio hops. This enables better coverage with less transmit power and, in many cases, a redundant path is also available. MAP is connected to core network through wired of wireless link.

The traffic control protocol shares the radio resources and routes the traffic through the "adhoc" established network. The protocol takes care of fair allocation of the channels. As a consequence every node has a reasonable understanding of its neighbouring nodes . This knowledge is then used to determine the radio resource usage as well as aiding in the traffic routing. Routing decisions can target to shortest paths, shortest delays, lowest transmit power or to avoid congested areas.

At the initial phase a mesh-network may need a small number of seed-nodes to generate a certain level of coverage. Every new node increases the coverage for potential newcomers and the existing terminals can be more often re-routed to optimize the network operation. When the network becomes denser the hop lengths will on average become shorter because more multihop connections can be applied. As a consequence transmit power levels can be lowered or the modulation method changed to increase hop-capacity.

When the network capacity becomes more and more loaded especially on hops near the access point network loading can be relieved by providing another node with a new backhaul link to turn it into a new core network access point. This will divide the mesh-network into two mesh clusters with more capacity available near the access-point and possibly also resulting shorter individual hops.

4.2.4 Modulation methods and coding rates

Mesh systems employ similar modulation techniques to those for P-MP systems. Both single carrier and multi-carrier formats are employed. Adaptive modulation techniques can be used in a similar manner to P-MP systems.

Table 1 presents typical bit rates using different modulations and coding rates for multicarrier transmission format Orthogonal Frequency Division Multiplexing (OFDM) using several modulation and coding alternatives such as BPSK, QPSK and 16 QAM and even up to 64 QAM with several coding rate alternatives (e.g. 1/2 and 3/4).

Table 1: Typical multicarrier coding rate and bit rate characteristics

Modulation	Coding rate	Coded bits per OFDM symbol	Data bits per OFDM symbol	Nominal bit rate (Mbit/s)
BPSK	1/2	48	24	6
BPSK	3/4	48	36	9
QPSK	1/2	96	48	12
QPSK	3/4	96	72	18
16 QAM	1/2	192	96	24
16 QAM	3/4	192	144	36
64 QAM	2/3	288	192	48
64 QAM	3/4	288	216	54

The values in table 1 are from IEEE 802.11a [8] and are specified for WLANs but can be used as indication of achievable capacity with different modulations and coding rates when about 20 MHz radio channel is used. Modulation method and coding rate can be changed according to the hop length when new routing is required.

4.2.5 Power control

Adaptive transmit Power Control (APC) is used in a mesh FWA system to select the lowest possible power required for communication to the receiving node i.e. to the neighbour node available to bypass the data packets towards the network access point. Thus the denser a network becomes, the lower transmit power may be used.

Transmit power in a newly established network may need to be higher to provide initial connectivity of the targeted area. Over time, as customers are added, the average transmit power will drop.

4.2.6 Services

The full range of typical FWA services can be delivered over a mesh-network.

4.3 Coverage and deployment

4.3.1 Coverage probability for omni-directional systems

If the probability to have a connection between any random points (fixed link probability) is z and m is the number of nodes in cluster, the probability to have a connection in a mesh network is:

$$P = 1 - (1 - z)^m$$

It can be seen that this probability approaches 100 % very fast with increasing number of nearby nodes (see figure 2).

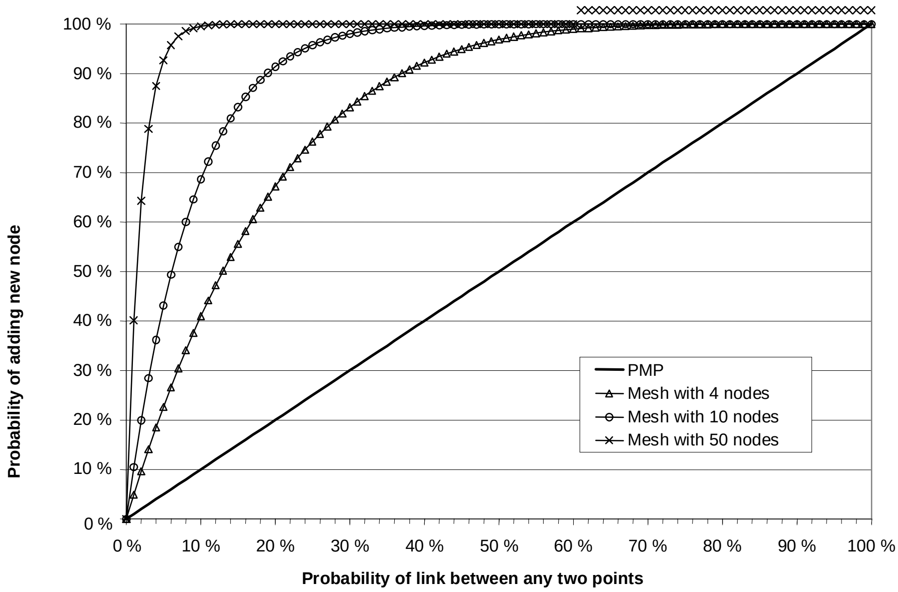


Figure 2: Increase of the coverage probability, the number of MESH nodes being as a parameter

The coverage probability increases rapidly as the number of nodes in the mesh-cluster increases and makes the turning up of new low loss paths more and more probable for new nodes.

In reality the probability of reliable link between any two points is not typically equal but depends on used system parameters: transmit power, antenna gains and receiver sensitivity. It is also affected by the attenuation of a link depending on distance between the two points and antenna heights.

Some practical values of link probabilities as a function of distance between two points with typical parameter values are shown in figure 3. The path loss is calculated here using extension of the Okumura empirical model applied in ref CEPT/ECC/ Report 33 [7] briefly described also in clause 8.1.1. The bit rates and receiver thresholds are listed in table 108. Mesh-node antenna heights are 9 m in this calculation and there may be some doubts of applying this path loss model to so low antenna heights. The result shown in figure 3 is , however, indicative and justifies the conclusions based on figure 2.

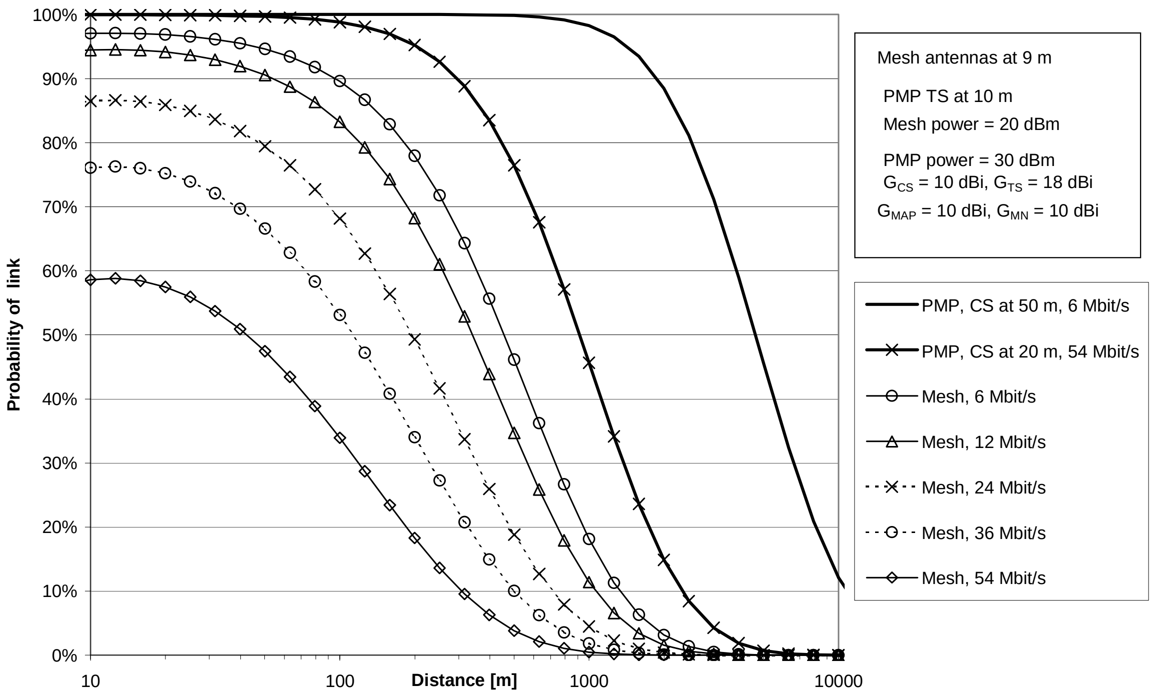


Figure 3: Probability of reliable link as a function of hop length for some typical P-MP and mesh systems parameters assuming path loss according extension of Okumura empirical propagation model.

4.3.2 Frequency usage

In omni-directional mesh systems deploying clusters of operation, frequency reuse can be implemented either in cellular pattern so that each mesh cluster (the domain within which traffic is routed to/from access point) reserves one channel. Optional solution would be that radios which are subject to each others' interference shall mutually agree the channel and timeslot assignments. In this case even one channel will be sufficient to cover a large geographical area, but the average capacity available to each end user would be low.

In directional mesh systems the internal frequency planning tends to be dynamic. It is viewed as another degree of freedom for allocating resources across the mesh network along with time slot allocation and antenna direction (and hence traffic routing). This possibility to re-use frequencies considerably increases the ability to support simultaneous users. The increase is to the first order, proportional to the inverse of the square of the antenna beamwidth.

4.4 Backhaul connection

In a mesh network, traffic from core networks can be inserted at any convenient node. Thus the probability of finding such a station near to a convenient core network access point is much higher. A link into the mesh can then be made using identical equipment and operating in the same frequency band as all the other links. Like other mesh links, these can be short and use low power.

Alternatively, combined use of P-P and P-MP systems could be envisaged as Mesh network backhaul to provide high-quality-high-bit-rate access to the areas where mesh-solution is implemented (see figure 4). P-MP might be able to the use the same frequency band as mesh-network but then coexistence must be ensured by careful frequency planning.

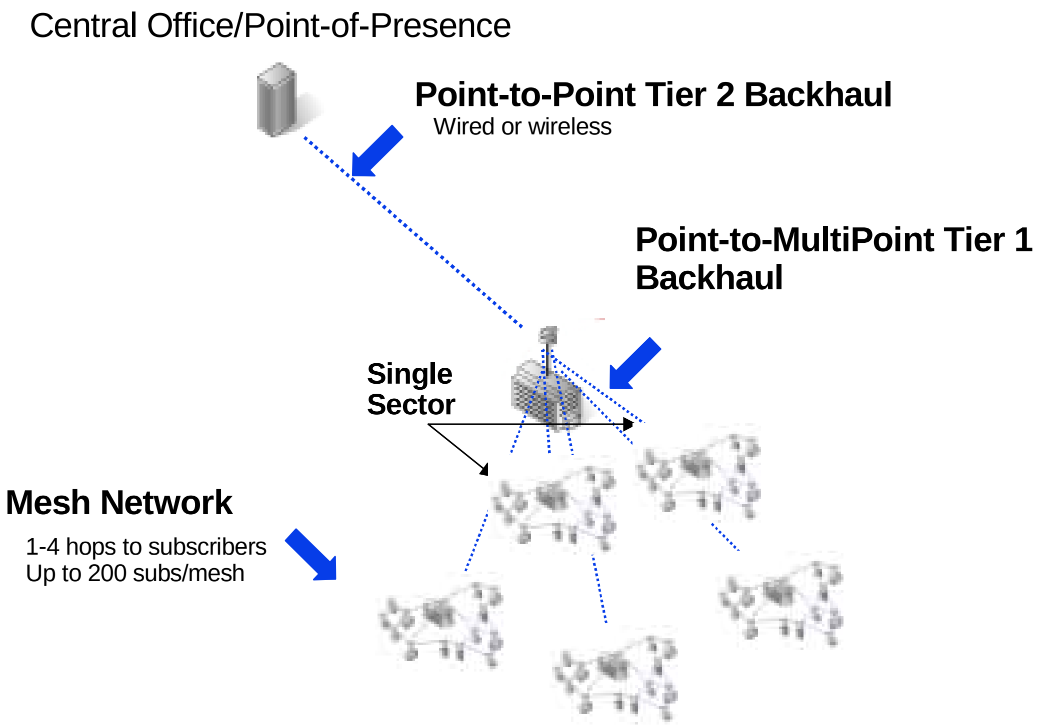


Figure 4: An example of possible mesh network and its backhaul connections

5 System parameters, capacities, hop lengths

5.1 System parameters

Table 2: Some common omni-directional mesh system parameters

Parameter	Typical values	Notes
Maximum Tx power	20 dBm (peak average ratio 6dB)	Actual power is dependent upon link length
Mesh antenna type	Omnidirectional	Directional or sector in special cases
Mesh antenna gain	10 dBi	
Transmit power range	25 dB	With respect to Max EIRP of 1W
Modulation	OFDM multicarrier with adaptive BPSK to 64 QAM	Code rate ≥ 1/2, adaptive selection of modulation and coding
Receiver threshold	-82 dBm BPSK 1/2 -81 dBm BPSK 3/4 -79 dBm QPSK 1/2 -77 dBm QPSK 3/4 -74 dBm 16 QAM 1/2 -70 dBm 16 QAM 3/4 -66 dBm 64 QAM 2/3 -65 dBm 64 QAM 3/4	6 Mbit/s (in 20 MHz) 9 Mbit/s 12 Mbit/s 18 Mbit/s 24 Mbit/s 36 Mbit/s 48 Mbit/s 54 Mbit/s
Duplex Type	TDD	
RF-channelization	20 MHz, 10 MHz, 5 MHz (28 MHz, 14 MHz, 7 MHz)	

Table 3: Some common directional mesh system parameters

Parameter	Typical values	Notes
Maximum Tx power	23 dBm for QPSK 19 dBm for 16 QAM 15 dBm for 64 QAM	Actual power is dependent upon link length
Mesh antenna gain	10 dBi to14 dBi	Not including radome and implementation losses of up to 3 dB
Antenna 3 dB beamwidth	22,5°	
Transmitter TPC	> 19 dB	With respect to Max EIRP of 2 W
Modulation	Single carrier QPSK to 64 QAM	12,5 Msymbols/s
Receiver threshold	-87 dBm for QPSK -80 dBm for 16 QAM -74 dBm for 64 QAM	
Duplex Type	TDD	But operation in FDD based channel arrangements possible
RF-channelization	20 MHz, 10 MHz, 5 MHz (28 MHz, 14 MHz, 7 MHz)	

5.2 Hop lengths and transmission performance

In outdoor environment the hop lengths are highly dependent on the effective path loss exponent values between routes. Two extreme cases i.e. modulation methods BPSK(1/2) and 64 QAM(3/4) are taken into account and the assumptions are indicated in table 2.

The line-of-sight path loss is equal to PL = 43,3 dB + 20 $\log_{10}(d)$ at 3,5 GHz. In sub-urban environments the average path loss exponent is typically about 2,8 with the antenna heights of mesh nodes giving rise to a path loss equation PL = 43,.3 + 10 n $\log_{10}(d)$. But an intelligent routing system can always select the best routes to be used and the actual average path loss exponent will be closer to that of line-of-sight (n = 2). If we assume that the mesh can utilize routes with propagation exponent n = 2 to 2,5 it would mean 300 m to 1000 m hop lengths for 64 QAM and over 1000 m hop lengths for BPSK in the example above (see figure 5). Maximum line of sight distances are 8,6 km by BPSK (1/2) and 1,2 km by 64 QAM (3/4) corresponding paths with propagation exponent equal to 2.

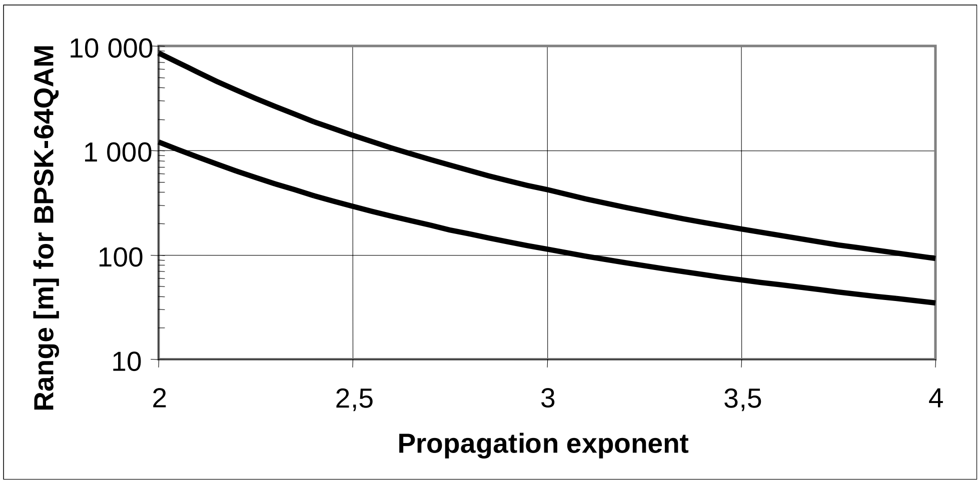


Figure 5: Hop lengths as a function of path loss exponent

6 Frequency plans

6.1 Frequency bands and RF-channels

Frequency bands allocated for FWA-use between 3 GHz and 11 GHz; 3,5 GHz [9], 3,7 GHz [10], 10,5 GHz [11] as summarized also in reference [1].

The following channelling alternatives are recommended by CEPT:

- RF-channelization for P-P: paired channels: 1 MHz, 75 MHz, 3 MHz, 5 MHz, 7 MHz, 14 MHz or 28 MHz
- RF-channelization for P-MP: paired blocks of width N × 0,25 MHz for frequency bands 3,5 GHz and 3,7 GHz and N × 0,5 MHz for 10,5 GHz, where N is an integer.

Recommended duplex-separations of paired channels or blocks are 50 MHz or 100 MHz in the bands 3,5 GHz and 3,7 GHz and 350 MHz in 10,5 GHz band.

Mesh-system may utilise any of these alternatives.

Table 4: Details of frequency bands which have been considered within CEPT

Frequency band	Band limits	Transmit/receive spacing (applies to channels/blocks)
3,5 GHz	3,4 GHz to 3,6 GHz	50 MHz or 100 MHz, CEPT/ERC Rec. 14-03 [9]
3,7 GHz	3,6 GHz to 3,8 GHZ	50 MHz or 100 MHz CEPT/ERC Rec. 12-08 [10]
10,5 GHz	10,15 GHz to 10,3 GHz paired with 10,5 GHz to 10,65 GHz	350 MHz, CEPT/ERC Rec. 12-05 [11]

In addition interest has grown in the possibilities for licence exempt (or lightly licensed) FWA deployment in the band 5,725 to 5,875 MHz. Although studies are underway to examine these possibilities, mesh systems are equally suited to operation in this band.

6.2 RF-channelling

In common with FWA P-MP systems adequate spectrum resources are required to adequately plan mesh system deployments making best use of characteristics that maximise efficiency and throughput thereby maximising active user density. Similar considerations exist concerning channelization with regard to deliverable system capacity objectives. Whilst directional mesh systems tend to use spectrum resources dynamically across the entire network, omni-directional mesh networks can employ a frequency re-use arrangement similar to P-MP systems for clusters of operation.

As an example for omni-directional mesh systems, the available total frequency band is about 200 MHz at 3,5 GHz and 3,7 GHz and 300 MHz (150 + 150 MHz) at 10,5 GHz. If 4/1 frequency reuse can be applied (see clause 8.3), the required band per system should be at least $2 \times 2 \times 7$ MHz but preferably $2 \times 4 \times 7$ MHz to guarantee adequate transmission capacities and also get a real coverage without excess interferences.

7 Coexistence using Omni-Directional antennas

7.1 Co-channel coexistence calculations in adjacent area

The target is to study the situation in case where part of the band in question is allocated to mesh-type of equipment. In co-channel analysis the target is to solve the minimum distance required between P-MP cell and mesh cluster to allow uncoordinated usage of these two systems. The required minimum distance to be solved here is defined to be between the P-MP CS and closest mesh node, i.e. in the edge of mesh cluster, as indicated in the figure 6 showing the geometry of co-channel coexistence situation.

Mesh systems with omni directional antennas typically have a structure made of "cells" each of which uses a single frequency. The system traffic is managed by choosing appropriate TDD timeslots. The cell frequency can be reused where co-channel interference is low enough (i.e. where building and terrain losses between different users are sufficient).

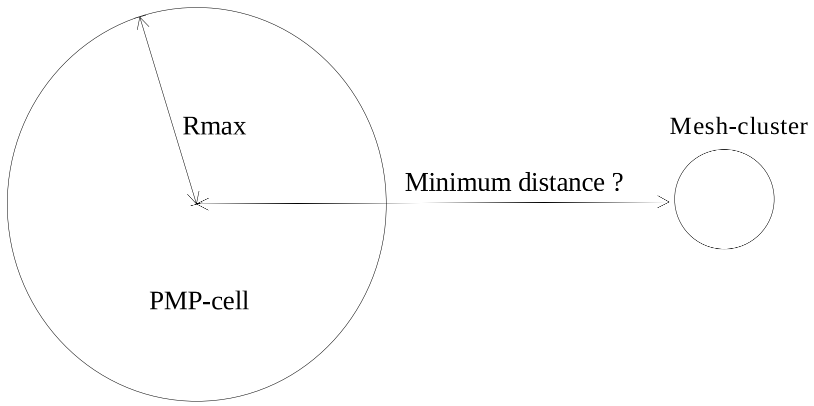


Figure 6: Geometry of co-channel coexistence of mesh cluster and P-MP cell (Rmax ≈ 20 km [7])

Parameters of P-MP systems for the calculations at 3,5 GHz are shown in table A.1 of annex A. P-MP-systems apply typically FDD and Mesh-systems apply TDD.

For mesh systems EIRP = -10 dBW/MHz is calculated using 10 MHz spectrum width, 20 dBm transmit power and 10 dBi antenna gain.

7.1.1 Co-channel interference from Omni-Directional Mesh to P-MP CS

The minimum distance required between P-MP CS and closest mesh node can be estimated from figure 7 as in reference CEPT/ECC/ Report 33 [7] the calculations are based on free space loss and spherical diffraction model. The mesh node has a typical EIRP value of -10 dBW/MHz. The interference limit is -146 dBW/MHz corresponding I/N = -10 dB.

Conclusion:

The required minimum distance estimated from figure 7 is around 28 km to 42 km for EIRP value -10 dBW/MHz and depending on antenna heights. Typical mesh node antenna heights are around 5 m to 10 m and P-MP CS antenna heights 20 m to 50 m.

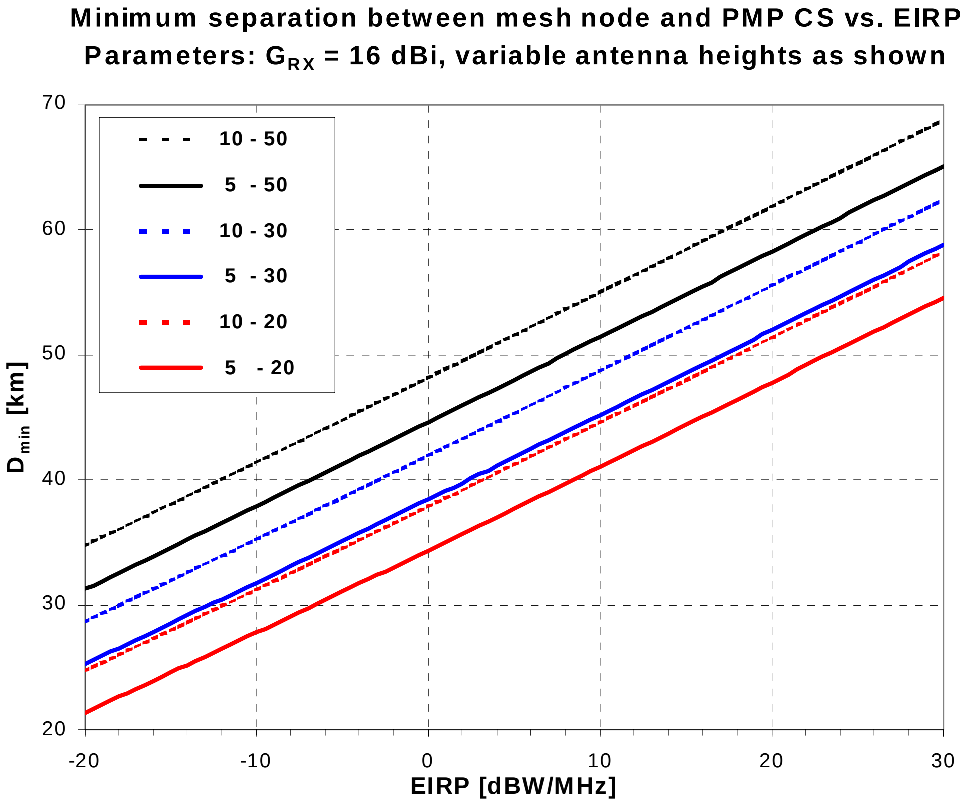


Figure 7: Minimum separation of P-MP CS and closest mesh node

7.1.2 Co-channel interference from Mesh to P-MP TS

In this clause the Interference Scenario Occurrence Probability (ISOP) values of closest mesh node interfering P-MP terminal stations assuming that the minimum separation distances according to clause 7.1.1 are used. The ISOP values are derived using SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) simulation tool, described shortly in annex 4, with 20 000 terminal station sites in every simulation.

The ISOP values for different P-MP terminal station antenna classes [2] are given in table 5 using same antenna height combinations and corresponding minimum separation distances as in clause 7.1.1 and assuming P-MP cell size of 20 km. TS antenna height of 10 m is used. The free space loss and spherical Earth diffraction are considered and I/N criteria of -10 dB is used in the simulations.

Conclusion:

Co-existence case "mesh to P-MP CS" requires longer separation distances than the case "mesh to P-MP TS" when TS antenna classes 3, 4 or 5 are used. With TS antennas TS1 and TS2 cases with interference scenario probabilities > 0 are counted for distances 28 km to 36 km. With distances 38 km or longer the counted ISOP values are 0 which means that case "mesh to P-MP CS" determines the coordination distance.

Table 5: Probability of interference from closest mesh node with max power to randomly selected P-MP terminal station ("Mesh to P-MP TS")

P-MP CS antenna height (m)	Mesh antenna height (m)	P-MP CS to mesh cluster edge distance (km)	ISOP with TS1	ISOP with TS2	ISOP with TS3	ISOP with TS4	ISOP with TS5
20	5	28	14,69 %	3,29 %	0,00 %	0,00 %	0,00 %
20	10	32	15,05 %	3,40 %	0,00 %	0,00 %	0,00 %
30	5	32	5,92 %	0,00 %	0,00 %	0,00 %	0,00 %
30	10	36	6,35 %	0,00 %	0,00 %	0,00 %	0,00 %
50	5	38	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
50	10	42	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %

7.1.3 Co-channel interference from P-MP CS to Mesh

The result of the analysis presented in clause 7.1.1 can be applied to the interference case "P-MP CS to mesh" Typical P-MP EIRP is 8 dBW/MHz but an "effective" EIRP value shall be used for this case which is obtained scaling the EIRP with Rx antenna gain difference (-6 dB in this case). The effective EIRP is therefore 8 dBW/MHz to 6 dBW/MHz = 2 dBW/MHz.

Conclusion:

The resulting minimum coordination distances from figure 7 in this case are 36 km to 50 km depending on the selected antenna heights.

7.1.4 Co-channel interference from P-MP TS to Mesh

In this clause ISOP values of P-MP terminal station interfering the closest mesh node assuming that the minimum separation distances (P-MP to Mesh) according to the clause 7.1.3 are used (from figure 7 with EIRP = + 2). The ISOP values are derived using SEAMCAT simulation tool with 20 000 terminal station sites in every simulation. The ISOP values for different P-MP terminal station antenna classes EN 302 085 [2] are given in the table 6 using same antenna height combinations and corresponding minimum separation distances as in clause 7.1.3 and assuming P-MP cell size of 20 km. TS antenna height of 10 m is used. The free space loss and spherical Earth diffraction are considered and I/N criteria of -10 dB is used in the simulations.

Table 6: Probability of interference from randomly selected P-MP terminal station with max power to closest mesh node ("P-MP TS to Mesh")

P-MP CS antenna height (m)	Mesh antenna height (m)	P-MP CS to mesh cluster edge distance (km)	ISOP with TS1	ISOP with TS2	ISOP with TS3	ISOP with TS4	ISOP with TS5
20	5	36	11,93 %	1,79 %	0,00 %	0,00 %	0,00 %
20	10	40	13,39 %	1,77 %	0,00 %	0,00 %	0,00 %
30	5	40	4,73 %	0,00 %	0,00 %	0,00 %	0,00 %
30	10	44	5,26 %	0,00 %	0,00 %	0,00 %	0,00 %
50	5	46	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
50	10	50	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %

Conclusion:

Co-existence case "P-MP CS to mesh" requires longer separation distances than the case "P-MP TS to mesh" when TS antenna classes 3, 4 or 5 are used. With TS antennas TS1 and TS2 cases with interference scenario probabilities > 0 are counted for distances 36 km to 40 km. With distances 46 km or longer the counted ISOP values are 0 which means that case "mesh to P-MP CS" determines the coordination distance and therefore no additional coordination is necessary for terminals.

7.1.5 Summary of co-channel interference analysis

The required minimum distances between P-MP cell and mesh cluster to allowing uncoordinated co-channel coexistence of these two systems are summarised in table 7a.

Table 7a: Required distance between P-MP cell and mesh cluster

Co-channel adjacent area cases	EIRP	Required distance
Mesh-to-P-MP CS	-10 dBW/MHz	28 km to 42 km (depending on antenna heights)
Mesh-to-P-MP TS		< 28 km (TS2…) TS3 …TS5
P-MP CS-to-Mesh	+2 dBW/MHz (see note)	36 km to 50 km (depending on antenna heights)
P-MP TS-to-Mesh		< 36 km (TS2…) TS3…TS5
NOTE: Effective EIRP for this calculation only to apply the analysis in clause 7.1.1		

Due to lower EIRP of mesh nodes compared to P-MP systems the mesh topology is more vulnerable to interference in co-channel case between P-MP system and mesh cluster.

Compared with the required minimum distances between two P-MP CS stations which are 60 km to 80 km CEPT/ECC/ Report 33 [7], the mesh topology allows closer placement (36 km to 50 km depending on antenna heights) of uncoordinated P-MP and mesh systems.

7.2 Coexistence analysis between adjacent frequency blocks in the same area

The coexistence of a P-MP system and mesh system at 3,5 GHz band is considered in this clause. The SEAMCAT Monte Carlo simulation tool is used to determine the ISOP values for different cases. Operator A is having a FDD P-MP system and Operator B is using mesh topology with TDD. Both operators have a paired blocks of 2 × 14 MHz, which is divided into four channels of 7 MHz for both operators as depicted in figure 8. It is also assumed that a guard channel of 7 MHz is used between the frequency blocks of these two operators.

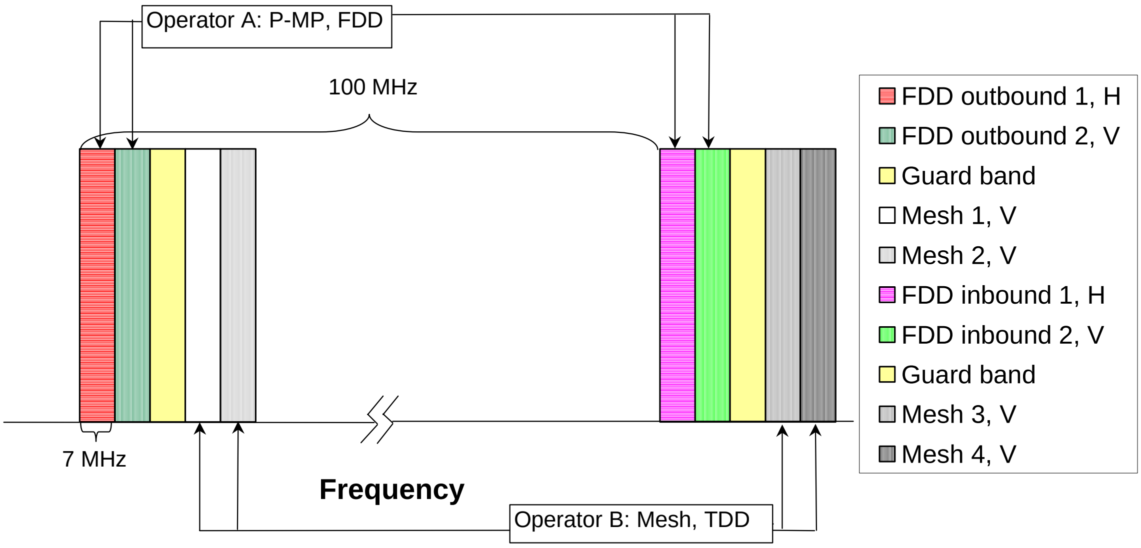


Figure 8: Frequency channels assumed to be used by operators A and B in the simulations of clause 7.2 (H and V mean horizontal and vertical polarizations)

Important factors here are the spectrum mask and the Net Filter Discrimination (NFD). The study shall cover both specified as well as typical values for these parameters. The parameters use in the calculation are summarized in table 7b.

Table 7b: System parameters used in the adjacent frequency block coexistence analysis

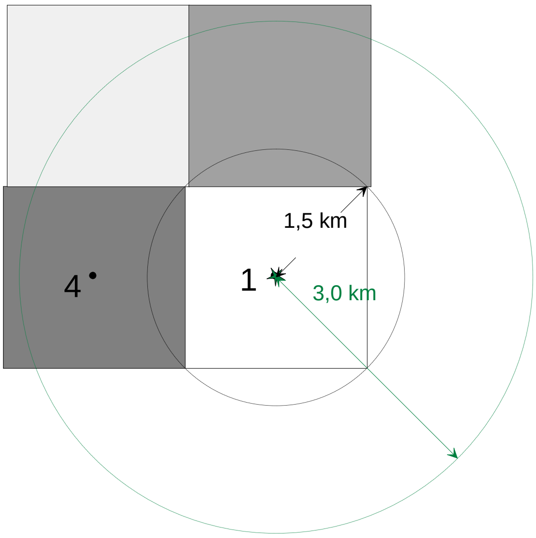
	P-MP (system D, typical 64 QAM)	Mesh (system G, typical OFDM 64 QAM)
Channel bandwidth (MHz)	7	7
Actual signal bandwidth BWtx = BWrx (MHz)	6	6
Transmitted Power at antenna input (dBm)	30 (CS and TS)	20
Receiver Noise Figure at antenna input (dB)	8	8
Receiver Noise Floor	-97,5	-97,5
Central station (CS) antenna type, bore-sight gain, height	CS3, 4 sectors, 16 dBi, 30 m	NA
Terminal antenna type, boresight gain, height	TS5, 18 dBi, 10 m	Mesh Node, omnidirectional, 10 dBi, 7,5 m
Tx power control	40 dB, 2 dB steps	-
Cell radius	3 km	1,5 km

The P-MP central station use sectored antenna with 4 sectors with opposite sectors using same channel. P-MP cell radius of 3 km and mesh cluster size of 1,5 km are assumed resulting equal non-overlapping coverage area for one P-MP sector and one mesh cluster.

Two different cases illustrated in figure 9 to be studied by the simulations (as geometrically extreme cases):

Case I: P-MP CS is in the middle of the interesting mesh cluster;

Case II: P-MP CS is in the edge of the interesting mesh cluster, i.e. P-MP CS in the crossing point of four mesh clusters using different channels.



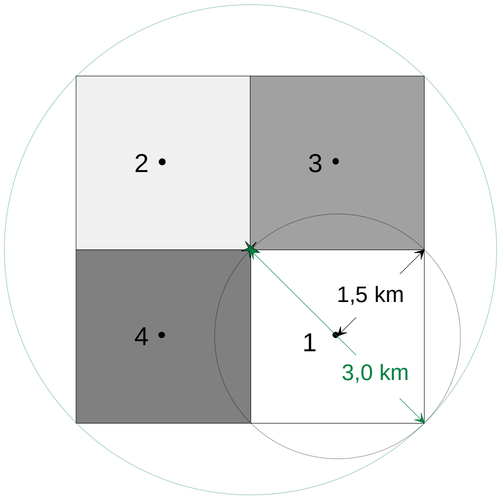


Figure 9: Geometry of the simulations of clause 7.2.
Case I in left graph ("Middle"), Case II in right graph ("Corner")

According to table A. of annex A the receiver Noise Figure of 8 dB has been used giving the noise floor at the P-MP receiver input -97,5 dBm. Same receiver Noise Figure and thus also same noise floor at receiver input is used also for mesh receiver.

The operation environment considered is suburban as a most prominent environment for mesh topology to be installed. The Okumura-Hata propagation model for suburban environment is used in the simulations.

SEAMCAT can calculate interfering received signal strength due to unwanted emissions and interfering received signal strength within the interferer bandwidth and attenuated by the receiver mask called blocking interference. Both unwanted interference and blocking interference are taken into account in the simulations presented in this clause.

The typical receiver selectivity curve shown in figure 10 is used for simulations. For unwanted interference the emission masks used are specified in EN 301 021 [1]. For P-MP system the mask of system D is used and for mesh the OFDM mask of system G is used (see figure 12). It is assumed that P-MP and mesh devices use adaptive modulations including the higher complexity modulation formats D and G (e.g. 64 states or equivalent). Mesh employs OFDM modulations and P-MP employs single carrier modulations.

The effect of using block-edge mask proposed in CEPT/ECC/ Report 33 [7] is also tested in the simulations assuming joint usage of block-edge mask and guard channel. The block-edge mask and frequencies of interested channels are shown in figure 11. The block-edge mask, proposed in ref CEPT/ECC/ Report 33 [7], gives absolute EIRP limits. In order to compare the absolute block-edge mask and emission masks D and G the scaled block-edge masks are given in figure 12. The EIRP density limit of -64 dBW/MHz corresponds power level of -35,5 dBm before antenna for mesh node and -41,5 dBm for P-MP CS.

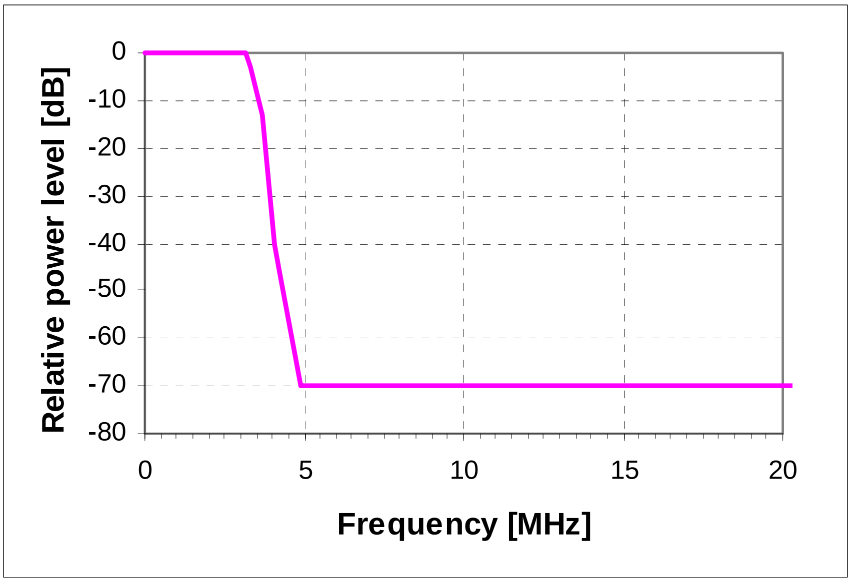


Figure 10: Typical receiver selectivity curve

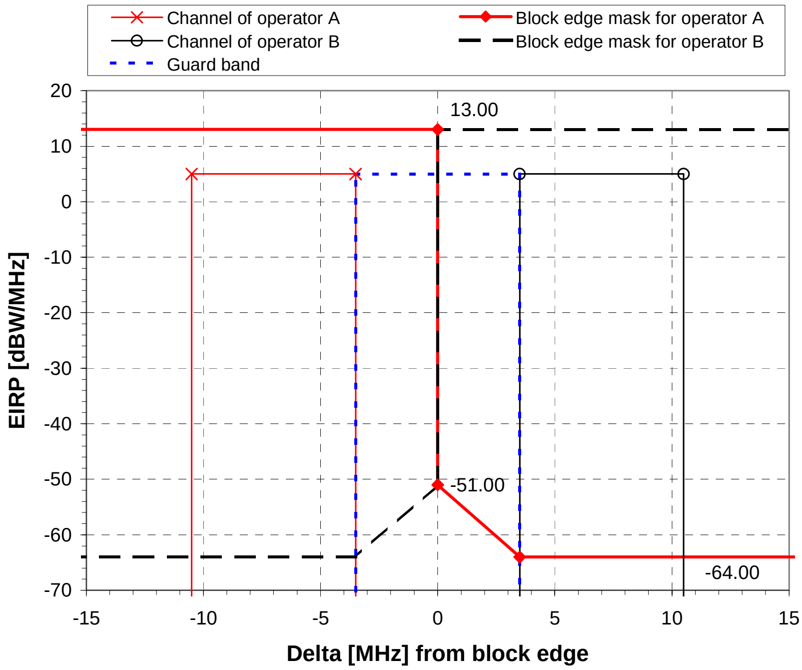


Figure 11: Block-edge mask and channels

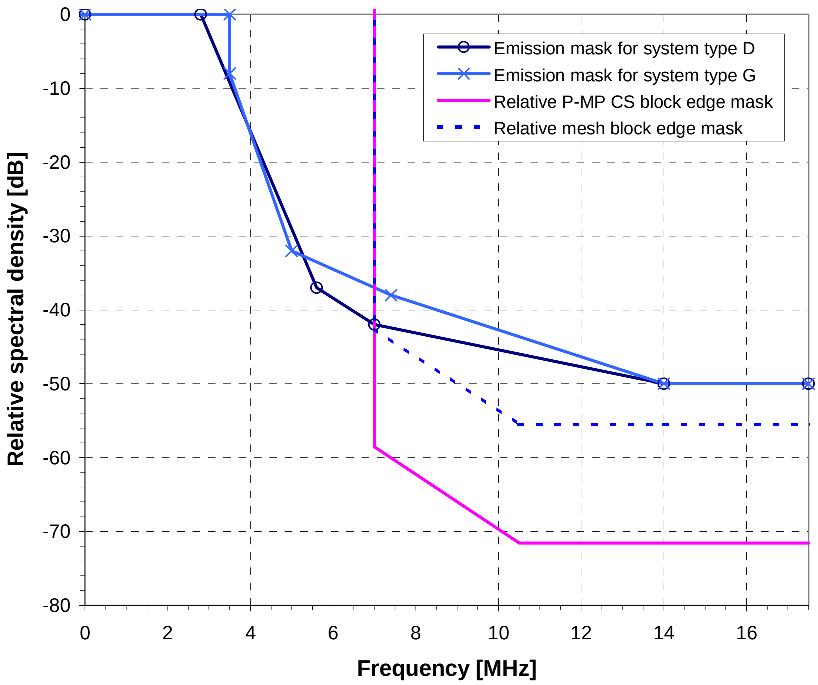


Figure 12: Masks used in the calculations

Relative block-edge masks for P-MP CS and mesh-node shown in figure 12 are derived by scaling from EIRP - mask proposed in ref [7] (see also figure 11). For PMP PMP CS the mask is scaled by 7,55 dBW/MHz and for mesh node by –8,45 dBW/MHz which are the EIRP-density values within the pass-band for these terminals.

7.2.1 Adjacent block Omni Mesh interference to P-MP CS

Referring to figure 8 the worst situation is from mesh cluster using channel 3 is interfering P-MP CS, which is receiving in FDD inbound channel 2. It is also assumed that both these channels use vertical polarization. The simulated Interference Scenario Occurrence Probability (ISOP) values for this worst situation are shown as a function of required C/(I+N) criteria in figure 13 and 14 without and with block-edge mask, respectively. As the opposite P-MP sectors are using same channels either of the two sectors receiving in FDD inbound channel 2 could be interfered, which is taken into account in the given ISOP curves.

The probability of interference situation is higher when P-MP central station is in the middle of mesh cluster (Cases I) since there are possible interferers in the main beam of P-MP CS antenna regardless of the orientation of the P-MP sectors and interferes are closer on average.

ISOP vs. C/(I+N) criteria curves can be used to estimate which modulation methods can be used in the interfered system to guarantee low enough, e.g. 1 %, ISOP values. The C/(I+N) criteria for uncoded single carrier and OFDM modulations are considered in clause 5.Without the block-edge the usage of uncoded 16 QAM modulation in P-MP terminal stations would result ISOP values about 1% depending on geometrical situation meaning that the usage of uncoded 16 QAM could be doubtful. Without the block-edge mask it would be safer to use uncoded QPSK or coded medium complexity modulation formats (16 states or equivalent) in P-MP terminal stations. With the block-edge mask proposed in CEPT/ECC/ Report 33 [7] used in mesh nodes the situation improves noticeably so that the usage of uncoded 16 QAM results ISOP values below 0,5 % and possibly even more complex modulations with coding could be used in P-MP terminal stations.

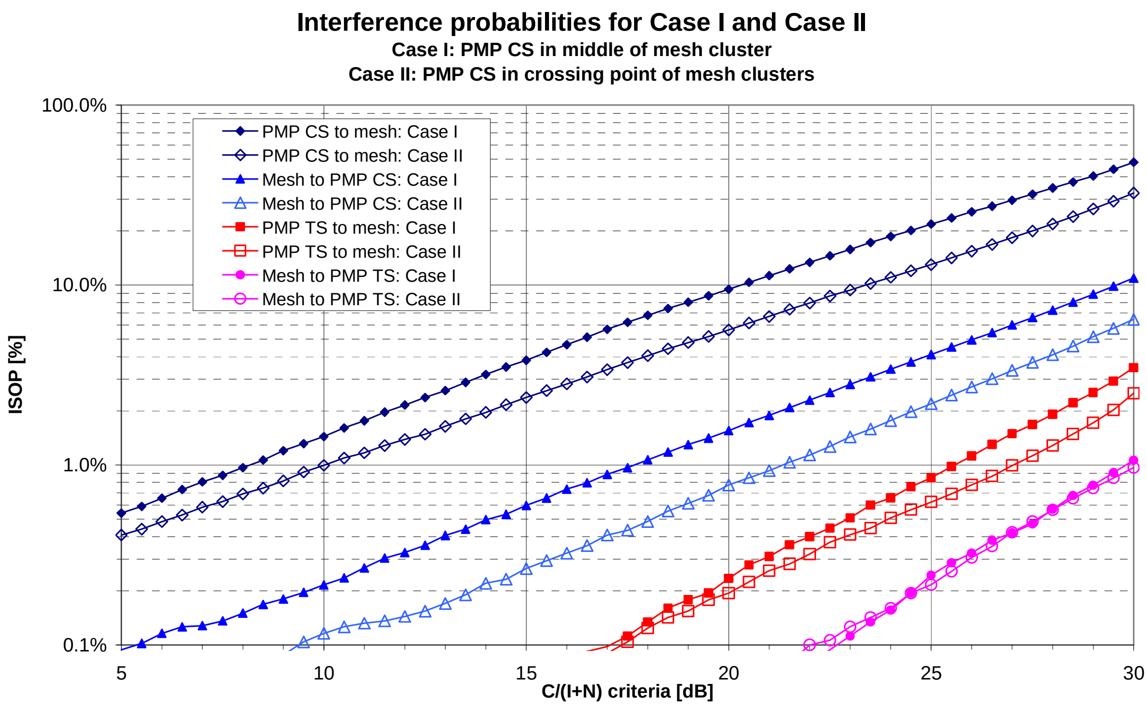


Figure 13: Interference occurrence probabilities as a function of C/(I+N) criteria using emission mask of EN 301 021 [1] for every cases

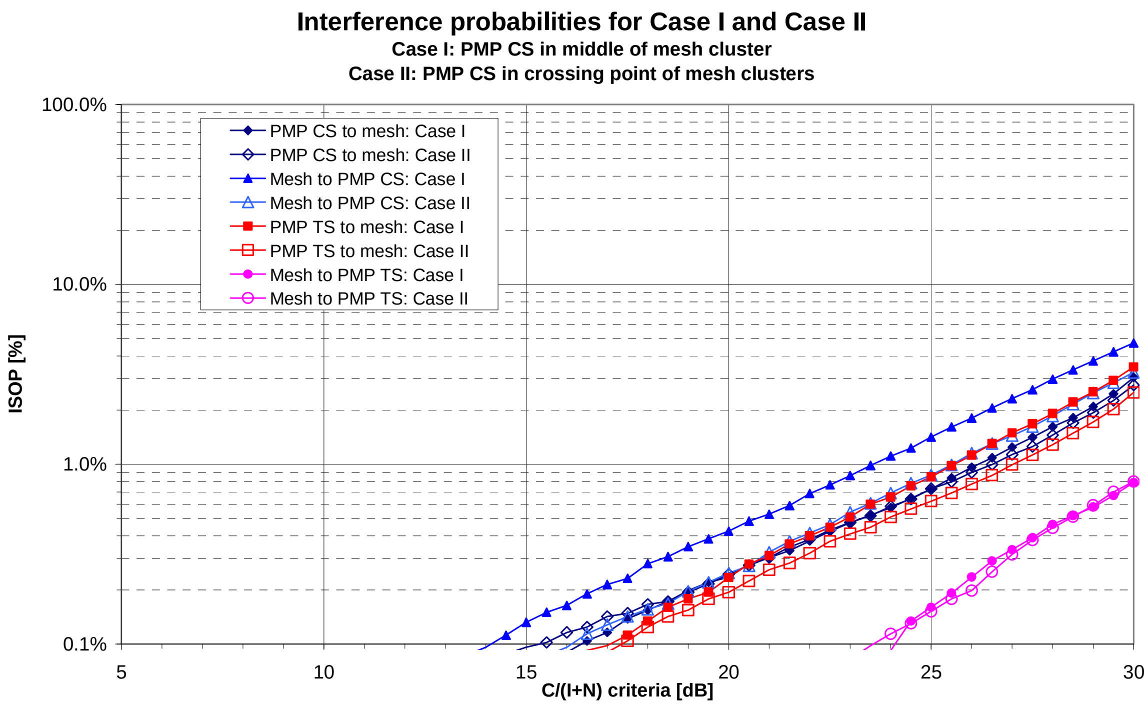


Figure 14: Interference occurrence probabilities as a function of C/(I+N) criteria using block-edge mask proposed in CEPT/ECC/ Report 33 [7] for P-MP CS and mesh and emission mask of EN 301 021 [1] for P-MP TS

7.2.2 Adjacent block Omni Mesh interference to P-MP TS

Referring to Figure 8 the worst-case interference situation is from mesh cluster using channel 1 and interfering with P-MP TS which is receiving in outbound channel 2. It is assumed that both of these channels use vertical polarisation. The simulated ISOP-values for this case are shown in Figures 13 and 14.

Mesh to P-MP TS interference probability is low enough even with modulations using many states requiring high C/(I+N) values. For example 26,5 dB is required by 64 QAM for BER level of 10^{-6} resulting ISOP values clearly below one per cent both with and without the block-edge mask. Thus, the noticeable improvement via usage of block-edge mask is not necessarily required in order to allow usage of higher complexity modulation formats (e.g. 64 states or equivalent) in P-MP central station.

7.2.3 Adjacent block P-MP CS interference to Omni Mesh

The worst-case interference situation according to figure 8 is from P-MP CS outbound channel 2 to mesh cluster at channel 1. It is assumed that both these channels use vertical polarization. The simulated ISOP-values for this worst-case situation are shown in figures 13 and 14.

In order to get ISOP values below 1 % in this case the mesh nodes could use only OFDM modulations with QPSK with code rate 1/2 without block-edge mask except some extreme cases. Block-edge mask will, however remarkably improve the situation allowing that even with OFDM with 64 QAM and coding rate 3/4 for which the ISOP values are below 0,7 % (see table 8).

7.2.4 Adjacent block P-MP TS interference to Mesh

The worst situation according to figure 8 is from P-MP TS using inbound channel 2 to mesh cluster using channel 3. It is assumed that both these channels use vertical polarization. The simulated interference occurrence probabilities are shown in figure 13.

P-MP TS to Mesh ISOP (interference scenario occurrence probability) is lower than 0,8 % for OFDM with 64 QAM and coding rate 3/4 (see figure 14 and table 8).

The block-edge masks proposed in CEPT/ECC/ Report 33 [7] for P-MP TS are looser than the emission mask of EN 301 021 [1], so the P-MP TS to mesh interference situation is not improved if these block-edge masks will be used.

7.2.5 Summary of the adjacent block same area coexistence analysis

Table 8 summarises the critical C/(I+N) values that would limit the Interference Scenario Occurrence Probability ISOP values below about 1 % with and without block-edge mask.

Table 8: The critical C/(I+N) values resulting Interference Scenario Occurrence Probability ISOP values below 1 % with and without block-edge mask

Adjacent frequency block same area	Critical C/(I+N) for ISOP < 1 % without block-edge mask	Critical C/(I+N) for ISOP < 1 % with block-edge mask
Mesh-to-P-MP CS	17,5 dB (uncoded QPSK)	23,5 dB (uncoded 16 QAM)
Mesh-to-P-MP TS	29,5 dB	> 30 dB
P-MP CS-to-Mesh	8dB (QPSK 1/2)	26 dB
P-MP TS –to-Mesh	25,5 dB	25,5 dB (64 QAM 3/4)

NOTE 1: Block edge mask together with guard channel as depicted in figure 11

NOTE 2: Refer to Annex C for the details of C/(I+N) -thresholds for the different modulation/coding alternatives.

Mesh to P-MP CS

Without the block-edge mask the ISOP situation <1% (C/(I+N) = 17,5 dB) allows the use of uncoded QPSK or modulation with more states using coding in P-MP terminal stations. With the block-edge mask the ISOP situation < 1 % (C/(I+N) = 23,5 dB) allows the usage of uncoded 16 QAM modulation but also higher modulations if coding is applied in P-MP terminal stations.

Mesh to P-MP TS

The ISOP situation < 1 % (C/(I+N) = 29,5 dB) allows the use of uncoded 64 QAM in P-MP central station with or without the block-edge mask.

P-MP CS to Mesh

Without block-edge mask the ISOP situation < 1 % (C/(I+N) = 8 dB) allows the use of QPSK with code rate 1/2 in mesh nodes except some extreme cases. With block-edge mask the ISOP situation < 1 % (C/(I+N) = 25,5 dB) allows the use of even 64 QAM with code rate of 3/4 in mesh nodes.

Without block-edge mask, coexistence between mesh and P-MP in adjacent frequency assignments in the same area is possible when one guard channel is used (see figure 8). However, the interference between P-MP central station and mesh nodes limits the usable modulations.

The usage of block-edge mask, proposed in CEPT/ECC Report 33 [7], together with an internal offset from the block edge, as depicted in figure 11 above, would remarkably improve the interference situation allowing usage of higher complexity modulation formats e.g. up to 64 states or equivalent if coding is applied but up to 16 QAM for uncoded P-MP in some extreme cases. The block-edge mask improves the coexistence of P-MP and mesh at adjacent blocks in the same area.

These conclusions are valid under the system parameter assumptions depicted in table 7b. Some of the P-MP system parameters used in this report (modulation , TS-antenna height, CS and TS antenna type) corresponding to a scenario close to omnidirectional mesh application for sub-urban rather than urban environment, may differ from CEPT/ECC Report 33 [7], hence further simulations may be required for other applications, environments or parameters of P-MP-systems.

8 Spectrum efficiency and frequency reuse considerations using Omni-Directional antennas

8.1 Spectrum efficiency and areal coverage calculations of a single mesh cluster

8.1.1 Path-loss models

The main propagation mode is assumed to be free space with diffraction over rooftops and multiple reflections from buildings. A number of empirical and physical models are used to characterise this behaviour at UHF frequencies, but unfortunately little is known about their application to the 3,5 GHz band. The commonly accepted description of the received field is a "locally random" variable with lognormal p.d.f. around a median value. The associated path attenuation, in dB, shows a Gaussian p.d.f, with mean value A_{50} and standard deviation σ. In this work we evaluate A_{50} using an extension of the Okumura empirical model of ECC Report 33 [7]. According to the method A_{50} is given by:

$$A_{50} = 147{,}376 + 29{,}83 \log_{10}(D) - 13{,}958 \log_{10}(h_c) - 29{,}466 \log_{10}(f) + 9{,}56 [\log_{10}(f)]^2 + \\ + [13{,}34 - 5{,}8 \log_{10}(h_c)] [\log_{10}(D)]^2 - [1{,}47 + 13{,}7 \log_{10}(f)] [\log_{10}(h_t) - 0{,}585)]$$

where D is the distance in km, h_c h_t the CS and TS antenna heights in meters and f the frequency in MHz. The standard deviation "σ" of A_{sh} is given by:

$$\sigma = 0{,}65 [\log_{10}(f)]^2 -1{,}3 \log_{10} (f) + A$$

With f in MHz, A = 5,2 dB (urban) or 6,6 dB (suburban).

8.1.2 Areal coverage comparison

In Figure 15 the mean values of coverage from 50 simulations are given for different services area radius and parameter values. The figure labels give the number of subscribers in the service area. For PMP-systems the terms 'low', 'middle', and 'high' refer to CS antenna heights of 20, 30, and 50 m, respectively. In a suburban environment the possible service area radius is few kilometres when considering coverage pergentages higher than 90%. As an example for coverage 95% mesh topology can allow larger service area than PMP system when number of subscribers is 50 or more. The number of subscribers is assumed to have no effect on the coverage of PMP system. It can be concluded that mesh topology can provide comparable or better coverage than PMP even with lower power levels, omnidirectional antennas and lower antenna heights as soon as the number of nodes is high enough.

The coverage and achievable capacities of P-MP cell and equal size mesh cluster is simulated in a suburban environment using extension of the Okumura empirical model. It is assumed that both P-MP and mesh system can use adaptive OFDM modulation with parameter values given in table 2. Mesh system is using omnidirectional antennas with gain of 10 dBi. P-MP CS is also using omnidirectional antenna with gain of 10 dBi and TS antennas are directional antennas with gain of 18 dBi. Transmitted power at antenna input is 20 dBm for mesh system and 30 dBm for P-MP system. In both P-MP and mesh system the same number of subscribers in a cell is assumed and the values considered are 20, 50 or 100. Since in P-MP system the CS antenna height is a critical parameter affecting the coverage area values. CS-antenna heights 20 m, 30 m and 50 m are used. P-MP TS antenna height is assumed to be 10 m while mesh node antenna height of 9 m is used both in Mesh Access Point (MAP) and Mesh Node (MN). This means that the mesh antennas are assumed to be not higher than 1 meter from the roof top level and for P-MP TS antennas could be mounted up to 2 m higher than roof top level.

In figure 15 the mean values of coverage from 50 simulations are given for different services area radius and parameter values. The figure labels give the number of subscribers in the service area. For P-MP-systems the terms "low", "middle", and "high" refer to CS antenna heights of 20 m, 30 m, and 50 m, respectively. In a suburban environment the possible service area radius is few kilometres when considering coverage percentages higher than 90 %. As an example for coverage 95 % mesh topology can allow larger service area than P-MP system when number of subscribers is 50 or more. The number of subscribers is assumed to have no effect on the coverage of P-MP system. It can be concluded that mesh topology can provide comparable or better coverage than P-MP even with lower power levels, omnidirectional antennas and lower antenna heights as soon as the number of nodes is high enough.

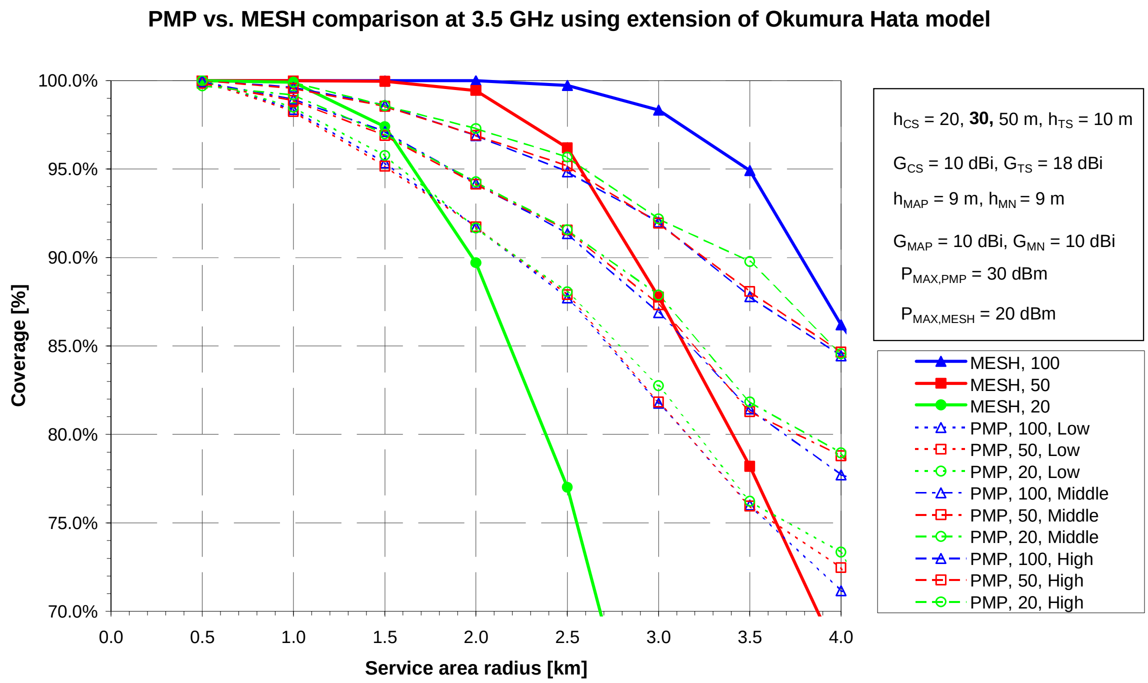


Figure 15: Simulated coverage of mesh and P-MP systems as a function of service area radius

8.1.3 Spectral efficiency comparison

The suitable figure of merit for spectrum usage in this example calculation is total capacity since both systems are using only one channel. For P-MP system the total capacity in each individual simulation is the mean of all achievable link bit rates. For mesh topology the throughput capacity is calculated as a weighted sum of achievable bit rates for hops directly connected to mesh access point and other hops nearer the mesh cluster edge divided by average number of hops to subscriber. Figure 16 shows the average of these total capacity values from all of the simulations.

With P-MP cell of 0,5 km radius practically all hops can use highest bit rate of 54 Mbit/s. As cell size increases increasing number of hops have to use lower bit rates and total capacity decreases. Note that the total capacity is calculated as an average of achievable links meaning that the decrease of coverage has no effect on this figure.

The total capacity of mesh topology is always lower than that of P-MP systems since all of the mesh nodes cannot have direct one hop-connection to mesh access point. With increasing service area the total capacity of mesh topology decreases faster than in P-MP case. For mesh topology two factors decrease the throughput capacity:

- Lower bit rates can be used on hops.
- Average number of hops to subscribers increases as more hops are needed to get coverage to nodes near the edge of mesh cluster.

In these total areal capacity results the number of subscribers in the service area has only a little effect and no effect at all from P-MP antenna height.

The capacity that can be guaranteed to each subscriber is also an interesting parameter. Figure 17 shows the results of average capacity that can be reached by all subscribers when they all are active simultaneously. In this consideration the decreased coverage had caused a little increase in the capacity per subscriber with highest cell radius values. This means that one should also bear in mind coverage aspect when interpreting these results. To emphasise the role of coverage the capacity results of mesh topology is given only for areas having coverage higher than 85 %. Actual capacities of active users will probably be significantly higher since it is unlikely that all subscribers are simultaneously active. Activity time of users could be estimated to be less than 0,5 %.

In this case the achievable aggregate capacity of mesh network is about 1/4 to 1/2 of P-MP system due to multihop nature of mesh network.

This result applies only for noise limited case where the interference of possible other P-MP cells or mesh clusters is not analysed but it is expected that P-MP will suffer more from interferences than mesh due to higher CS-antennas. Also mesh nodes use on average lower transmit powers and mesh-network therefore benefit from lower overall interference levels. An indicative spectrum efficiency comparison in dense interference limited network is shown in clause 8.3.2.

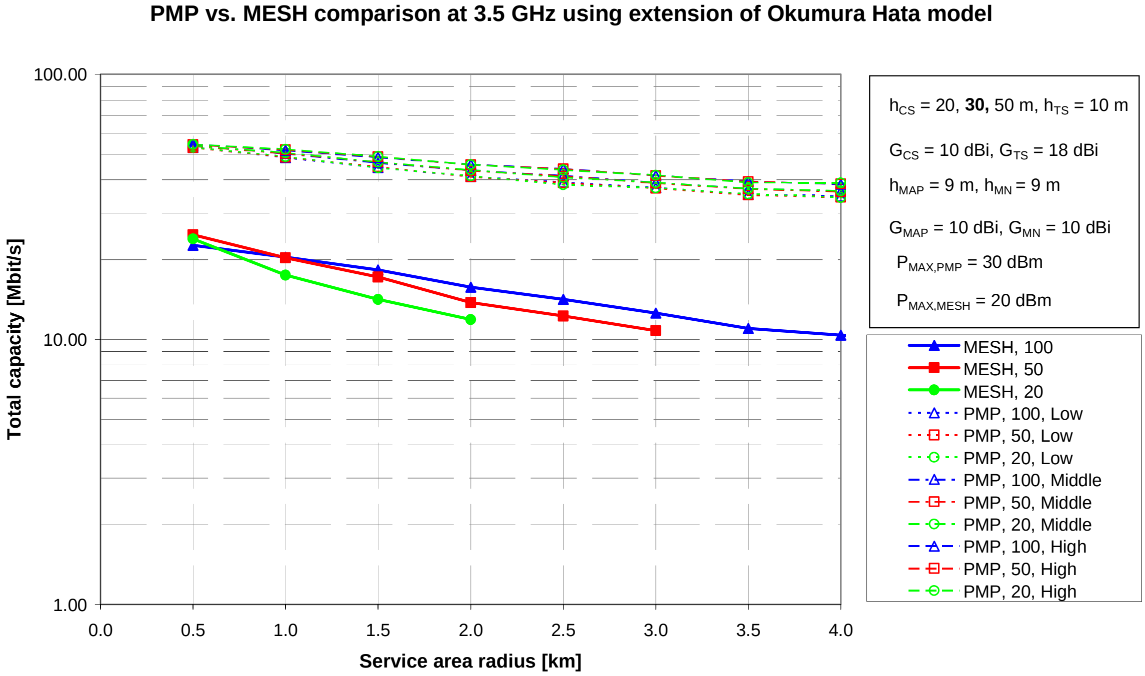


Figure 16: Total capacity of mesh and P-MP systems as a function of service area radius

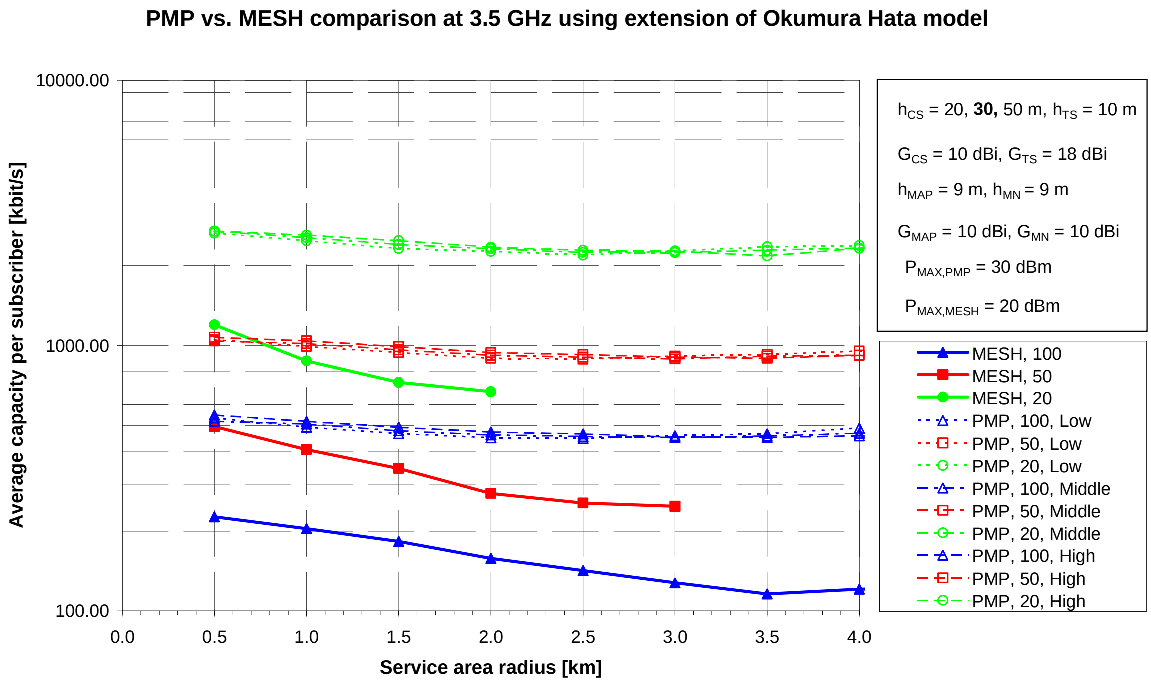


Figure 17: Average capacity per subscriber of mesh and P-MP systems as a function of service area radius

8.1.4 Comparisons

The coverage and achievable capacities of P-MP cell and equal size mesh cluster was simulated in suburban environment using extension of the Okumura empirical model. Simulations were performed for the case without possible surrounding P-MP cells or mesh clusters causing interference, meaning that these comparison are valid only for early deployment of these systems. These simulations included few practical factors which are favourable for P-MP systems:

- P-MP terminal stations used directional antennas;
- P-MP system used higher transmitted powers;
- the path attenuation levels of P-MP systems are lower due to higher antenna heights especially at central station.

Even with these assumptions mesh topology has comparable or better coverage than P-MP systems. With mesh topology the achievable capacity is around 1/4 to 1/2 of P-MP capacity with equal frequency channels and adaptive modulations assumed to be used in both systems. See also clause 8.3.2.

8.2 Traffic routing and control

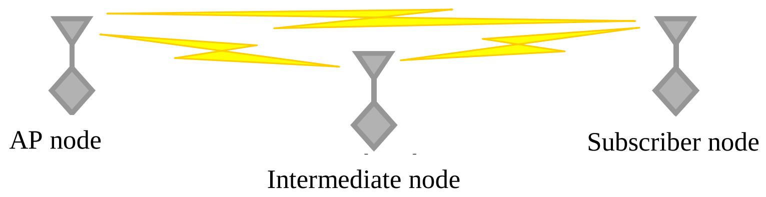


Figure 18: Use of intermediate node to increase coverage and throughput

The mesh system tends to apply short low loss hops rather than long and possibly more obstructed hops. This together with the ability to automatically select proper modulation method for the route and adapting to the available hop quality makes performance improvement over a traditional single hop case. The improvement is seen in increased throughput and in decreased interference generation in the vicinity.

As a simplified example of this routing advantage can be given a two hop line-of-sight connection having normal free space loss radio path characteristics. The 6 dB advantage assuming that the intermediate node is in between the mesh access point and subscriber means that 18 Mbit/s instead of 6 Mbit/s can be used for the connections (first 18 Mbit/s from mesh access point to the intermediate node and then 18 Mbit/s forwarded from the intermediate node to the subscriber vs. 6 Mbit/s directly from the mesh access point to the subscriber). The throughput is thus increased by 50 % and the interference generation is reduced by 33 % due to the reduced total time required by the higher rate connection. The spectrum mask is the same for the two cases, there is only less redundance in the higher rate case.

For obstructed paths (path loss exponent higher than two), the benefit is even bigger than described above. The assumption behind table 9 is that the needed receiver sensitivity for different bit rates is according to table 2. For the line-of-sight cases 6 dB equals doubling the distance. If the path loss exponent is 3, doubling the distance equals 9 dB change in the needed signal-to-noise ratio.

Table 9: Throughput comparison for direct links versus multihop routes

Case	Path loss exponent	Direct link modulation rate	Number of intermediate forwarders	Multihop modulation rates	Effective multihop throughout	Multihop throughput advantage
1	2	6 Mbps	1	18 Mbps	9 Mbps	50 %
2	2	6 Mbps	2	24 Mbps	8 Mbps	33 %
3	2	6 Mbps	3	36 Mbps	9 Mbps	50 %
4	3	6 Mbps	1	24 Mbps	12 Mbps	100 %
5	3	6 Mbps	2	36 Mbps	12 Mbps	100 %
6	3	6 Mbps	3	54 Mbps	13,5 Mbps	125 %

In the mesh-network most of the nodes must transmit and receive data coming from their neighbouring nodes in addition to their own user data and the available capacity is divided between all these needs. Some of the capacity is also needed for overhauling of the system (e.g. for preamble, scheduling, inter-link guard time, acknowledging, retransmits and other overheads). In a practical scenario the user data portion can be assumed to be 65 % to 75 % of the total capacity. There can also be different user groups within a mesh cluster, receiving more or less bandwidth and service e.g. business and residential subscribers.

The guaranteed capacity within a mesh cluster depends on the total number of customers in each user group, distribution in terms of number of hops to the customers and number of channels available. A general worst case formula for determination of the guaranteed capacity for the different subscriber groups can be written as:

$$B \cdot W_{bg}(b_1 + 2b_2 + 3b_3 + 4b_4) + C \cdot W_{rg}(c_1 + 2c_2 + 3c_3 + 4c_4) \le \eta R$$

Where B = total number of the business users within the mesh cluster:

W_{bg} = guaranteed capacity for business users (voice+data).

b_1 = 1-hop proportion of the business users.

b_2 = 2-hop proportion of the business users, etc.

C = total number of the residential users within the mesh cluster.

W_{rg} = guaranteed capacity for residential users (voice+data).

c_i = i-hop proportion of the residential users (i = 1, 2, 3, 4).

η = efficiency factor (percentual overhead proportion removed).

R = modulation rate [Mbps].

NOTE: That the sums Σb_i and Σc_i must be equal to one.

This is a worst case formula because it assumes that only one channel is available within a mesh cluster and that single channel can be used only in one hop at a time. The formula also assumes that all the users are actively using the capacity at all times. The average capacity and peak capacity are thus much larger.

A typical scenario would be upto 50 subscribers in total, 10 business plus 40 residential. Let us assume that both of them have a hop-distribution 35 %, 45 %, 15 % and 5 % for the 1-, 2-, 3- and 4- hop cases, and three times more capacity is allocated for each business user. Then the worst case guaranteed capacity would be 135 kbps for the residential customers and 405 kbps for the business customers provided that the efficiency factor is 0,75 and the modulation rate is 24 Mbps.

8.3 Frequency reuse considerations

8.3.1 Multichannel configurations

The mesh network dimensions can be adaptively scaled based on the use of the power control and routing algorithms. The total capacity per unit area can increase at nearly linear rate with increasing density. The scaling down of the microcells around the nodes permits efficient reuse of the RF-spectrum throughout the region. There can be sectorized antennas in the mesh access point sites (as indicated in the figure 19a). In that case the mesh access points are at the corner points of the mesh cluster. The Mesh topology and one frequency reuse scheme examples are depicted in figures 19 and 20.

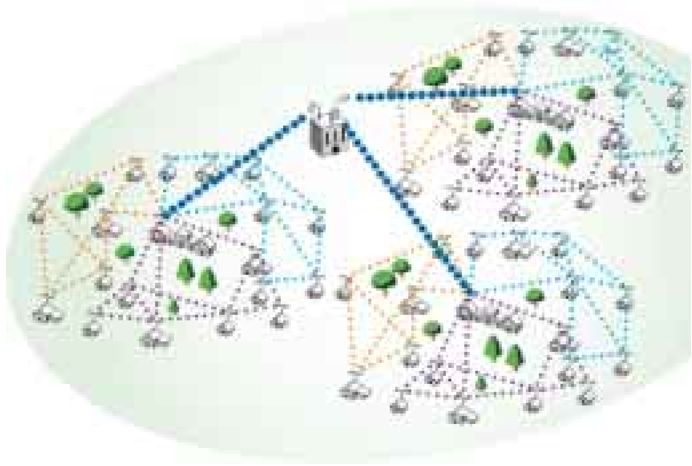


Figure 19: Example of nine mesh clusters with backhaul connections so that in each Mesh access point site have three Mesh access points

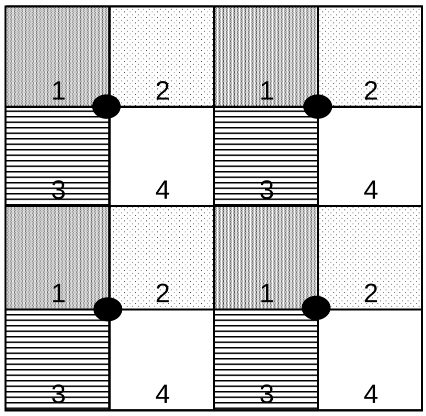


Figure 20: Example of use of channels in different mesh clusters. Mesh access point sites are marked with black circles and each containing four Mesh access points

In last mile access we can easily see that TDD applications have high bit/s/Hz spectral efficiency. In the same application FDD device would have to reserve a given part of spectrum even if there is no traffic to send. This fact is driving also voice-carrying trunk networks towards all-IP-solutions.

Frequency reuse in mesh topology relies on intelligent allocation of channels and timeslots. The available slots must be shared with mutual co-operation between terminals within the neighbourhood of the terminal, which is going to transmit. Each node has a distinct configuration of neighbourhood nodes.

In the first frequency reuse consideration only one channel is used within a mesh cluster and automatic routing and traffic control avoids traffic collisions in the mesh cluster meaning that only one node in mesh cluster can transmit at any time. The mesh network is taking into use the best hops in each geographical area and thus making the spectrum efficiency optimization by utilizing its hop selection algorithms. Therefore, within each mesh cluster the selected hops on average have lower path loss exponent than what is the median path loss exponent in the operating environment. This has two consequences:

1) the choice of hops reduces the needed transmit power;

2) the mean path loss exponents in interfering signals are higher than those of selected paths. As shown in figure 11 the difference in equal lengths can be several decibels.

The analytical calculations assuming different path loss exponents for selected hops and interfering signals shows that the frequency reuse scheme consisting of four channels like the one in figure 20 can be used. With the parameters of table 10 the bit rates up to 24 Mbit/s can be used, meaning that highest usable modulation scheme is 16 QAM with 1/2 coding.

8.3.2 Effects of inter-cell interferences (Example)

Since the Mesh Access Points energy need only be receivable in a fraction of the cell, as other nodes forward traffic to the edges of the Mesh Cluster, the interference level generated by the Mesh Access Point outside its Mesh Cluster is low due the following two facts:

- Propagation: Antennas are installed low and therefore interferences are attenuated by obstacles;
- Radiated Power: Low power used due to short hops.

Though the capacity in a single cell is lower for mesh devices, the substantially lower power levels, as well as the lack of elevated BS stations, allow substantially lower frequency re-use factors. Alternatively, it allows for lower inter-cell interference levels and hence less interference-limited capacity reduction. Both effects ensure that the capacity of a network, consisting of many cells, can be roughly equivalent to that of P-MP architectures.

Figure 21 shows the interference levels at twice the cell-radius for both P-MP and mesh systems, as well as the distance required to obtain a probability of interference less than 1%. For P-MP BS sectors, a front-to-back rejection of 40 dB is assumed. Interference is defined as power levels exceeding I/N = -6 dB, which is equivalent to a degradation in link budget of 1 dB.

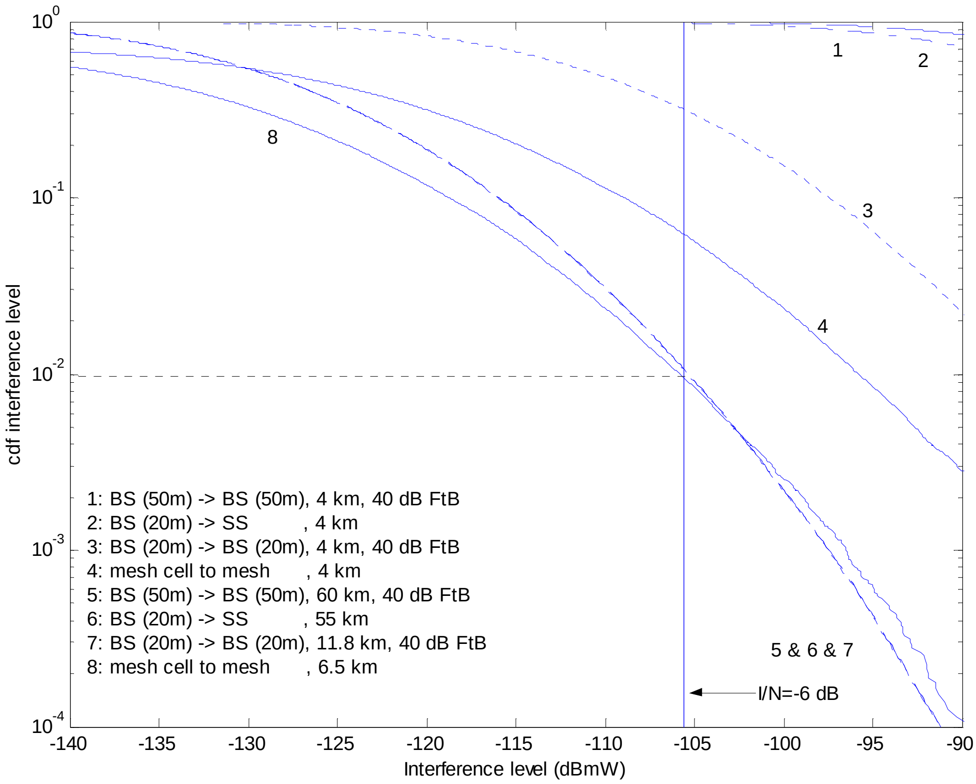


Figure 21: Inter-cell interference probability (2 km radius cell, 100 mesh nodes per sector)

9 Coexistence using directional antennas at subscriber stations

Mesh systems with directional antennas do not have a cell-like structure. Each node can communicate with a number of surrounding nodes and each node can pass on information to others. Traffic is thus routed via one or more repeaters to reach its destination. Each mesh node can assign traffic in one of a number of directions, choose one of the available frequencies and timeslots. This allows efficient reuse of spectrum over a wide coverage area. More details of the principles of this type of mesh system can be found in TR 101 939 [3].

9.1 Description of the analysis

The simulation tools used for this analysis are similar to those described in IEEE 802.16.2-REVa [14] for higher frequency bands, the only changes being the values of the system parameters. These have been adjusted to be typical of mesh systems operating in the frequency range 2 GHz to 11 GHz.

Mesh systems in this frequency range use antennas that vary in beam-width from approximately 20° to 120°. The P-MP system is assumed to use a 90° sector antenna at the base station and a narrow beam antenna at the subscriber station. Interference from the mesh system is aggregated and computed at the P-MP base-station or subscriber station.

The parameters used in the co-channel modelling are as follows:

- Frequency 3,5 GHz/10,5 GHz;
- Mesh dimensions: 10km × 10km;
- Mesh antenna beamwidth: 22,5° to 150°;
- P-MP subscriber antenna beam width: 14°;
- P-MP BS beamwidth: 90°;
- Rain fading: none and random storm cell conditions;
- Mesh link length range: 50 m to 3 500 m;
- Height of BS above surrounding terrain: 45 m;
- Height of SS above surrounding terrain; typically up to 20 m;
- Mesh node density: 50/sq km
- Mesh Tx power: max 23 dBm;
- Mesh antenna gain: 10 dBi;
- P-MP hub antenna gain: 10 dBi;
- P-MP SS antenna gain: 14 dBi;
- Mesh link data rate: 50 Mbit/s;
- ATPC: Yes;
- Rayleigh terrain factor: 5 to 20 (low suburban to dense urban);
- Maximum height of mesh node above rooftop: 0,2 m.

The nature of directional mesh systems requires a Monte Carlo methodology to produce probability distributions for interference levels between systems, each iteration laying out a different random model of a mesh system, based on a specified range of parameters.

The simulator models a mesh system as a series of links, laid down in a random pattern in a rectangular coverage area. The dimensions of the system and the link density can be varied as required, as can the parameters of the radio equipment and antennas. Each link is assigned a length between a defined minimum and maximum length, with all link lengths having equal probability.

The P-MP BS sector is placed in the most severe position and pointed directly at the mesh. In a mesh network, there are potentially multiple interferers on each channel, so that the signal from all possible contributing stations must be added together at the victim station. The geometry is shown in figure 22.

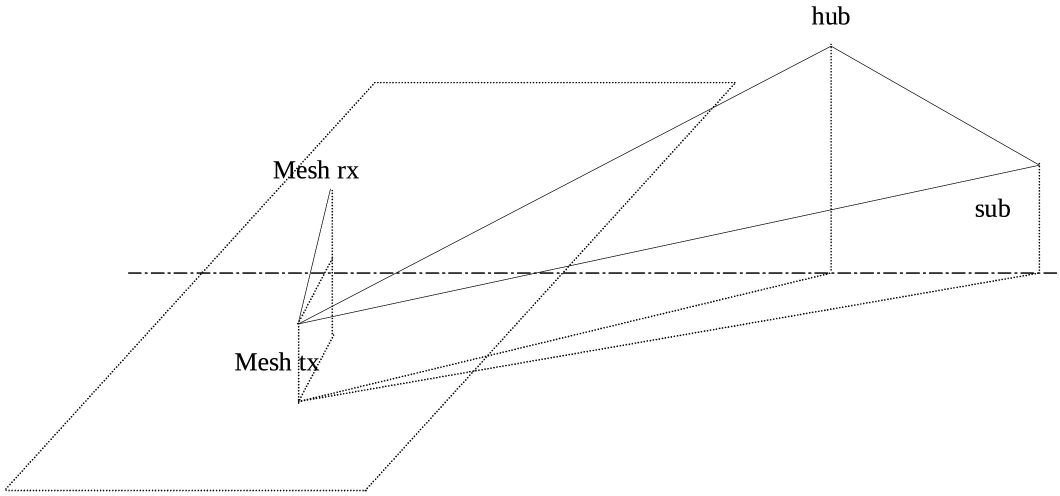


Figure 22: Interference geometry

The simulation tool used for this analysis is similar to that described in IEEE 802.16.2-REVa [14] the only changes being the values of the system parameters. These have been adjusted to be typical of mesh systems operating in the frequency range 2 GHz to 11 GHz.

9.2 Co-channel interference between Directional Mesh and P-MP CS

9.2.1 Co-channel interference simulations

The analysis requires the use of a Monte Carlo simulation technique, to evaluate the interference from a mesh system to a P-MP system. In the other direction, a simpler analysis is possible, since there is normally only a single interferer.

Mesh systems are deployed on or near rooftops, in order to make use of building and terrain losses and thus improve frequency reuse. This feature also improves coexistence with other systems and typically reduces the coordination distance. When one system is a mesh and the other system is P-MP, the P-MP central station interference dominates, due to the wide beam antenna and greater antenna height above surrounding terrain. Table 10 shows simulation results for central station interference (the worst case), for a range of urban and suburban environments. The Rayleigh factor R characterises the distribution of building heights. A factor of zero indicates free space paths (no buildings).
A factor of 5 is characteristic of a semi-rural environment with mostly very low buildings, whilst a factor of 20 typifies a city environment.

The simulation runs were carried out using frequencies of 3,5 GHz and 10,5 GHz. Results for systems operating in licence exempt bands may also be of value but take no account of any sharing etiquettes that may be deemed necessary to operate successfully in range of other FWA systems or to allow inter-service sharing. These etiquettes would presumably modify the random sampling of available frequencies and path directions to some extent.

Table 10 shows a selection of results for central station interference from the simulation runs. Each run comprised 10,000 trials, in which the mesh layout was varied between iterations.

Table 10: Directional Mesh to P-MP CS - Co-channel

Frequency	Mesh antenna beamwidth	R (Rayleigh Factor for building heights)	D (Mesh to P-MP distance)	Interference level
3,5 GHz	25 degrees	20	15 km	< -114,5 dBm/MHz (see note1)
3,5 GHz	45 degrees	20	25 km	< -114,5 dBm/MHz
3,5 GHz	45 degrees	5	50 km	< -114,5 dBm/MHz
3,5 GHz	45 degrees	0	100 km	Exceeds required threshold
3,5 GHz	120 degrees	5	50 km	< -114,5 dBm/MHz
3,5 GHz	90 degrees	5	50 km	< -114,5 dBm/MHz
10,5 GHz	25 degrees	20	12 km	< < -114,5 dBm/MHz (see note 2)
10,5 GHz	120°	5	12 km	< < -114,5 dBm/MHz

NOTE 1: the value of -114,5 dBm/MHz corresponds to the interference limit for multiple interferers used in the IEEE recommended practice, IEEE 802.16.2-REVa [14].

NOTE 2: the results at 10,5 GHz were several dB better than at 3,5 GHz. However, mesh equipment parameters for this frequency range are not accurately known, so that values have been estimated. It may therefore be preferred at the present time to use the 3,5 GHz guidelines for planning and coordination purposes.

The result for a Rayleigh factor of 0 is included only for comparison. It corresponds to an area with building of no height and is thus not realistic of an actual deployment.

9.2.2 Co-channel interference from Directional Mesh to P-MP TS

The analysis for directional mesh to P-MP TS is similar to that for CS interference, except that a different antenna pattern is used for the victim and antenna heights are generally lower (typically below 20 m). On this basis, the TS interference values were all found to be much lower than those for a CS at similar distances, so that the CS case dominates the requirement for coordination distance and values in table 10 are therefore appropriate.

Also, the alignment of a TS antenna with that of a directional mesh antenna has relatively low probability. The TS antenna always points towards its serving CS, so that the TSs nearest to the mesh face away from the mesh.

A directional mesh uses an intelligent configuration tool that can take account of incoming interference. This is initially aimed at mitigating self-interference within the mesh but will also reduce cases of external interference. The random simulation model is thus pessimistic.

9.2.3 Co-channel interference from P-MP CS to Directional Mesh

In this direction, a simple worst-case analysis is sufficient. A Monte Carlo simulation is not required. For comparable link range, the maximum EIRP is similar in each direction . This worst case analysis thus shows similar coordination distances to the reciprocal case of mesh to P-MP, based on the Monte Carlo analysis. However, a directional mesh uses an intelligent configuration tool that can take account of incoming interference. This is initially aimed at mitigating self–interference within the mesh but will also reduce cases of external interference. Thus, the interference case from a directional mesh with intelligent management of channels and timeslots will normally control the coordination distance.

9.2.4 Co-channel interference from P-MP TS to Directional Mesh

As for the reciprocal case the TS interference is normally much less significant than for CS. The coordination distances for CS thus dominate.

9.2.5 Conclusions of co - channel interference analysis

For the case of a directional mesh, the required distance is typically well below 50km and varies in the example calculations from 12 km to 50 km, dependent on the assumptions relating to building heights. A coordination trigger distance of 50 km is adequate and covers > 99 % of cases. The CS interference case dominates for all reasonable P-MP antenna heights.

For 3,5 GHz systems, the results show that with a Rayleigh factor of 5 or higher (describing building height distribution) a 50 km coordination distance is adequate. This corresponds to an environment with mostly very low buildings. In practice a Rayleigh factor of 15 or more is characteristic of urban and semi urban environments. Factors below 5 would be very exceptional, since mesh systems of the type described are only deployed on rooftops. A reduced coordination distance is clearly possible when a higher Rayleigh factor can be relied on, which should be the case for most environments. The worst-case interference is with the P-MP CS and all results tabulated cover this case.

For 10,5 GHz systems, the results are several dB better. However, the parameters for such systems are not well known and have been estimated.

Thus, it is concluded that a coordination distance between co-channel mesh and P-MP systems of 50 km is satisfactory. This is the distance beyond which inter-operator coordination need not be triggered. An equivalent value for P-MP to P-MP interference is 60 km to 80 km., derived in IEEE 802.16.2-REVa [14].

As can be seen, in practice a much shorter distance between co-channel systems will be possible in the great majority of cases.

9.3 Coexistence between adjacent frequency blocks in the same area

The analysis requires the use of a similar Monte Carlo simulation technique to that used for the directional mesh co-channel analysis, adapted to take account of the slightly different geometry and the possible need for guard band isolation. It evaluates the interference from a mesh system to a P-MP system. In the other direction, a simpler analysis is possible, since there is normally only a single interferer active at any one moment.

9.3.1 Adjacent channel interference simulations

As for the co-channel simulator, the mesh is modelled as a series of links, laid down in a random pattern in a rectangular coverage area. The dimensions of the system and the link density can be varied as required, as can the parameters of the radio equipment and antennas. Each link is assigned a length between a defined minimum and maximum length, with all link lengths having equal probability.

The victim CS or TS is placed in the centre of the mesh. The CS height can be varied, as can the antenna beamwidths of both TS and CS. Additional attenuation between the systems can be added to correspond to a chosen number of guard channels, including the case where adjacent channel operation is considered (no guard channel). Other aspects of the simulation method are the same as the co-channel case.

The interference target maximum level in the model is -114,5 dBm/MHz measured at the victim receiver input. A large number of trial runs of the simulator tool (typically 10,000) are used to generate a histogram of interfering signal against probability of occurrence. The number of guard channels is varied until the probability of exceeding the target threshold is sufficiently low. This is typically when a single guard channel is used, corresponding to a probability of much less than 0,1 %.

The parameters used in the same area modelling are as follows:

- Frequency 3,5 GHz/10,5 GHz;
- Mesh dimensions: 10 km × 10 km;
- Mesh antenna beamwidth: 22,5°;
- P-MP subscriber antenna beamwidth: 14°;
- P-MP BS beamwidth: 90°;
- Guard band: 0 or 1 channel (NFD of 24 dB or 45 dB);
- Rain fading: none and random storm cell conditions;
- Mesh link length range: 50 m to 3 500 m;
- Height of BS above surrounding terrain: 30 m;

- Height of SS above surrounding terrain: 20 m;
- Mesh node density: 50/sq km;
- Min spacing from P-MP system = 10 m;
- Mesh Tx power: max 23 dBm;
- Mesh antenna gain: 10 dBi;
- P-MP hub antenna gain: 10 dBi to16 dBi;
- P-MP TS antenna gain: 14 dBi to 20 dBi;
- Mesh link data rate: 50 Mbit/s;
- ATPC: Yes;
- Rayleigh terrain factor: 10 (urban/suburban);
- Maximum height of mesh node above rooftop: 0,2 m.

The parameters for 10,5 GHz systems are less certain than those for 3,5 GHz, since there are no known mesh systems available or in development in this band.

9.3.2 Adjacent block directional mesh interference to P-MP CS and TS

Table 11 shows a selection of results from the simulation runs. Each run comprised 10 000 trials, in which the mesh layout was varied between iterations.

Table 11: Simulator Results (same area case)

Frequency	Mesh antenna beamwidth	Victim station	Rain fading	R (Rayleigh Factor) (see note 2)	Number of guard channel s	Probability of exceeding the target threshold (see note 1)	Maximum level of interference
3,5 GHz	22,5°	CS (90°/10 dBi) at 30 m height	None	10	1	0	-105,9 dBm
3,5 GHz	22,5°	CS (90°/10 dBi) at 50 m height	None	10	1	0	-107,8 dBm
3,5 GHz	22,5°	CS (90°/10 dBi) at 50 m	Storm	10	1	0	-108 dBm
3,5 GHz	22,5°	CS (90°/16 dBi) at 50 m	None	10	1	0	-101,8 dBm
3,5 GHz	22,5°	TS (14°/14 dBi) (see note 3)	None	10	1	<0,01 %	-96,1 dBm
3,5 GHz	22,5°	TS (14°/14 dBi)	Storm	10	1	<0,01 %	-92,1 dBm
3,5 GHz	22,5°	TS (18°/20dBi)	None	10	1	0,13 %	-91,6 dBm
3,5 GHz	22,5°	TS (28°/14 dBi)	None	10	1	0,06 %	-98,3 dBm
10,5 GHz	22,5°	CS at 30 m height	None	10	1	0	-106 dBm
10,5 GHz	22,5°	CS at 50 m height	None	10	1	0	-107 dBm
10,5 GHz	22,5°	CS at 50 m height	Storm	10	1	0	-108 dBm
10,5 GHz	22,5°	TS (see note 3)	None	10	1	0,04 %	-96 dBm

NOTE 1: The target threshold value is -114,5 dBm/MHz (-101,5 dBm in 20 MHz). This corresponds to the interference limit for multiple interferers used in the IEEE recommended practice, IEEE 802.16.2-REVa [14].
NOTE 2: Building height distribution parameter; the impact of different Rayleigh factors is much smaller than in the co-channel, adjacent area case, because the majority of paths are LOS to the victim BS or SS, which are positioned above most of the surrounding clutter.
NOTE 3: The simulator assigns heights for TSs according to the Rayleigh model for building heights, placing each at a set height above the rooftop (in this case 0,2 m).
NOTE 4: Two example 3,5 GHz antenna types are included from CEPT/ECC Report 33 [7]

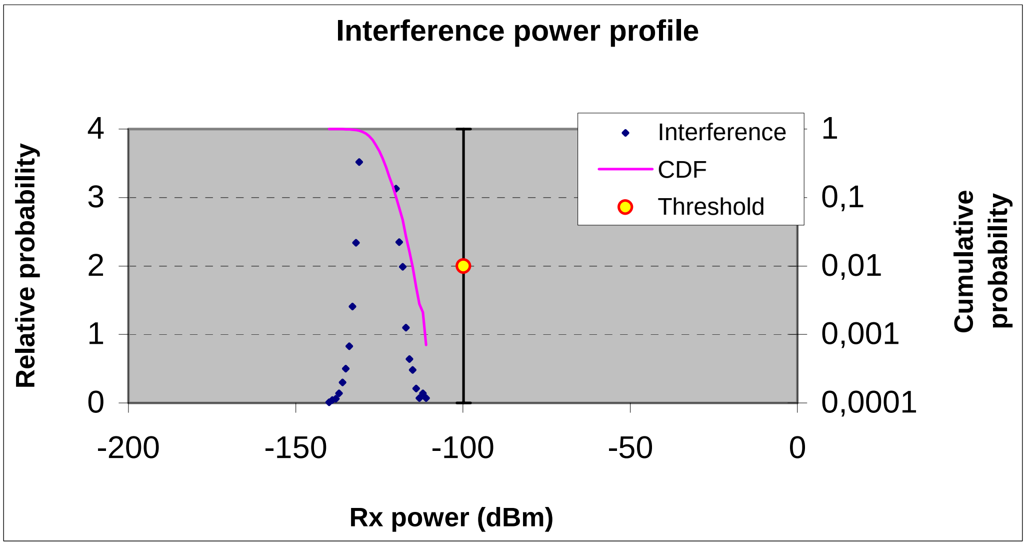


Figure 23: Probability distribution for CS interference at 45 m height, 1 guard channel, 10,5 GHz no rain

Figure 23 is a sample of the probability distribution generated by the simulator. Relative probability and cumulative probability are both plotted. It can be seen that all iterations of the simulator produce results below the target threshold, given a single guard channel between the mesh and P-MP systems. This is a typical result for CS interference.

In the case of TS interference, probability curves are wider and flatter, with most results giving lower interference but a very small number of cases having higher values. The number of cases giving values above the target interference level is negligibly small. These slightly different results can be explained by the narrow beams of both interferer and victim stations. Thus, alignment has low probability but in cases where this does occur, the interference may be higher than the CS (since the TS antenna has more gain than that of the CS).

9.3.3 Adjacent block directional mesh interference from P-MP CS and TS

Since the maximum EIRP in this direction is of the same order, the worst-case interference value is also similar. However, the probability of interference is normally significantly reduced because this type of mesh uses automated channel and timeslot assignment techniques that take account of self - interference and external interference appearing on operational channels. Thus the already low probability of interference will be further reduced in this direction.

9.3.4 Conclusions for the adjacent block same area coexistence analysis for directional mesh systems

A single guard channel of the same order as the mesh channel bandwidth will reduce interference to very low levels. The probability of interference above the ITU recommended aggregate limit of -114,5 dBm/MHz is lower than 0,05 % in the least favourable scenario identified.

Even with adjacent channel operation, the interference probability is still low 2,8 % in the example). Thus, a single guard channel guideline is satisfactory for directional mesh systems in this frequency range.

10 Spectrum efficiency and frequency reuse considerations using directional mesh systems

The analysis requires the use of a similar Monte Carlo simulation technique to that used for the directional mesh co-channel analysis, adapted to take account of the slightly different geometry and the possible need for guard band isolation. It evaluates the interference from a mesh system to a P-MP system. In the other direction, a simpler analysis is possible, since there is normally only a single interferer active at any one moment.

10.1 Modellling

The parameters used in the same area modelling are as follows:

- Frequency 3,5 GHz/10,5 GHz;
- Mesh dimensions: 10km × 10km;
- Mesh antenna beamwidth: 22,5°;
- P-MP subscriber antenna beamwidth; 14°;
- P-MP BS beamwidth: 90°;
- Guard band: 0 or 1 channel (NFD of 24 dB or 45 dB);
- Rain fading: none and random storm cell conditions;
- Mesh link length range: 50 m to 3 500 m;
- Height of BS above surrounding terrain: 30 m;
- Height of SS above surrounding terrain: 20 m.

10.2 Spectrum efficiency with directional mesh

10.2.1 Path loss models

In coexistence calculations for mesh systems with substantially directional antennas, a path loss model that takes account of building and clutter losses is useful. It is assumed here that building and terrain heights follow Rayleigh distribution, derived from [15].

For spectrum efficiency calculations it is useful to separate factors associated with resource management (antenna direction, frequency of operation and timeslot allocation) from propagation issues. A mesh with substantially directional antennas derives its improved spectrum efficiency and capacity from intelligent choice of these resources. Thus, an analytical model has been developed that assumes initially line of sight propagation between all mesh nodes. The improvements that arise as other parameters are varied can thus be easily distinguished.

10.2.2 Area coverage

A mesh with directional antennas operates as a unified system over large areas. There is no need to divide coverage into sub - areas or "cells" like P-MP systems. Indeed, to gain maximum advantage in terms of spectral efficiency it is preferred to manage resources over the entire network.

An estimate of the coverage probability of a mesh network using substantially directional antennas can be found in IEEE 802.16.2-REVa [14]. In the present document coverage probability is defined as the probability that a new subscriber randomly located within the nominal coverage area can be served from at least one of the existing node stations. The results were derived from simulation, using directional antennas and a terrain model to determine which paths are available LOS from existing nodes. Further analysis may be useful for lower frequency mesh systems, although the results are not likely to be much different. Directional mesh systems improve coverage probability because, even at low density, there are likely to be several possible system nodes within range of a new subscriber.

10.2.3 Spectral efficiency calculation example

The analytical model for spectral efficiency allows a number of parameters to be varied, as follows:

- Required minimum C/I ratio (possible building reflections ignored);
- Adjacent channel rejection (NFD);
- Antenna beamwidth;
- Max links per node;
- Average use of links per node;
- Number of timeslots per link path and overall;
- Node data bandwidth;
- Seed node density.

These factors are then used to calculate the maximum density of mesh nodes per unit area of coverage.

The following factors were used in the calculation for systems in the frequency range 2 GHz to 11 GHz.

Table 12: System parameters used in the analysis

Mesh Parameters	Value	Units
Carrier to interference ratio	40	Factor
Adjacent channel rejection	30	Factor
Beamwidth (-3 db)	22,5	Degrees
Max number of links per node	4	
Average used active links/node	3	
Time slots per link	2	
Max time slot pairs	32	
Bit rate per node (Duplex)	9	Mbit/s
Seed nodes	2	$1/km^2$

The results for a mesh with 22,5° beamwidth antennas and a range of numbers of available channels and average traffic rates per subscriber are shown in figure 24:

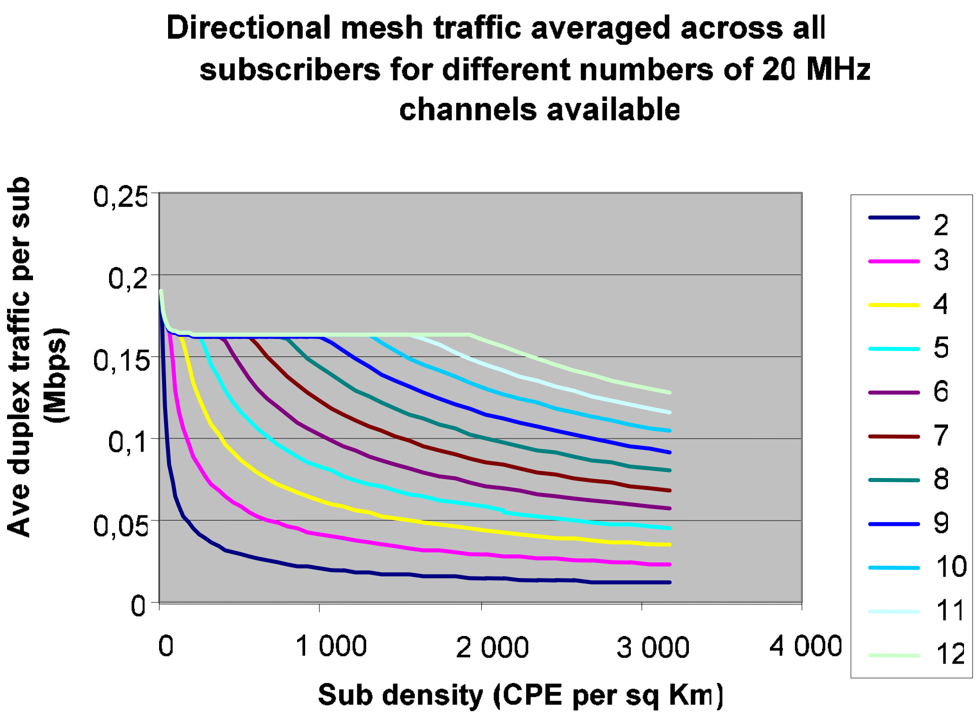


Figure 24: Directional Mesh traffic averaged across all subscribers for different numbers of 20 MHz channels available

It will be seen that even with relatively few available channels, a large user density is possible. In the extreme case of very small numbers of users, each with high data requirements, mesh systems give comparable results to P-MP. For all other cases, a mesh with directional antennas can provide very large capacity and spectrum efficiency gains, even before additional path losses (due to buildings and clutter) are taken into account. Whereas these additional losses can improve both P-MP and Mesh capacity, the impact on coverage is not similar. A directional mesh takes advantage of the obstructed paths by steering around them, using multiple hops. Thus, high spectral efficiency and very high levels of coverage.

10.2.4 Conclusions for directional mesh systems

Directional mesh systems, in which the antenna beamwidth is relatively narrow (typically less than around 25 degrees) offer improved spectral efficiency and coverage probability at the same time. Even with only a small frequency allocation, hundreds to thousands of active users per sq km ca be supported.

Coverage is not limited to sub-areas or "cells". A large area can be covered by a single interconnected mesh network. The size of the network is limited only by the ability to connect to convenient access points, with sufficient capacity to support the total end- user traffic demand.

11 Comparison with P-MP

The network topologies of the Mesh and P-MP networks are different. While there is a central station in a P-MP system, there is no highly centralized traffic control in a Mesh case and the connections can be multihop routes. This basic difference in the network architectures leads to many fundamental differences in the technical parameters and performance also. Some of the main differences are listed in the table 13.

Table 13: Comparison with P-MP

	MESH	P-MP
Type of routes	Meshed, always best routes selected	Radial from central station
Average path loss exponent	Typically near line-of-sight (selected routes by intelligent software)	Typically LOS but coverage reduced
Interference situation	Interferences on average see higher path loss exponent than 2	CS: sensitive TS: Directional antennas alleviate interference situation
Types of antenna	Access point: Omni antennas or sector antennas (or smart antennas) Other nodes: Omni antennas or directional antennas	CS: sectorized antennas TS: directional antennas
Location of antenna	Rooftop level	CS: typically high towers TS: typically rooftop level
Link range	Typically 100 m...few kilometres	Typically 100 m...over 10 kilometres
Power level and its control	Adaptive, low power levels due to short hops and selection of best hops	Adaptive at TS, high at CS
Modulation	Adaptive	Adaptive
User throughput	Moderate, depends on number of nodes within AP's control area and number of active users accessibility higher than P-MP	Moderate, depends on number of terminal stations (typically higher than in mesh)
System margin requirement	Low, margin monitored constantly and can be optimised	Medium (depends on hop length)
Robustness to link changes	Good, can be re-routed when needed	Rerouting difficult

12 Main conclusions

Good coverage can be obtained by mesh systems even by low link probability but it is paid by lower capacity because of multihop connections.

The capacity of mesh network, consisting of many clusters, will be roughly equivalent to that of P-MP cells due to either lower frequency re-use factor or less intra-system interference.

Mesh clusters can be placed closer (36 km to 50 km depending on antenna heights) P-MP CS than two P-MP CS (60 km to 80 km) in co-channel case. The reason for this follows from lower interference potential of mesh-systems due to lower EIRP and lower antenna heights.

Without block-edge mask, coexistence between mesh and P-MP in adjacent frequency assignments in the same area is possible when one guard channel is used. However, the interference between P-MP central station and mesh nodes limits the usable modulations.

The usage of block-edge mask, proposed in CEPT/ECC Report 33 [7], together with an internal offset from the block edge would remarkably improve the interference situation allowing usage of higher complexity modulation formats e.g. up to 64 states or equivalent if coding is applied but up to 16 QAM for uncoded P-MP in some extreme cases. Some of the P-MP system parameters used in this report may differ from CEPT/ECC Report 33 [7], hence further simulations may be required for other applications, environments or parameters of P-MP-systems.

Annex A: Basic data for coexistence analysis

Table A.1.1: Typical parameters of a FWA system (3,5 GHz) ECC Report 33 [7]

	System Type (according to typical ETSI definitions)	
	Type A (typical 4 state)	**Type B (typical 16 state)**
Frequency band (GHz)	3,41 to 3,6	3,41 to 3,6
Channel bandwidth (MHz)	7[1]	7[1]
Actual signal bandwidth BWtx = BWrx (MHz)	6	6
Transmitted Power at antenna input (dBm)[2]	30	30
Receiver Noise Figure at antenna input (dB)	8[3]	8[3]
CNR at 10^{-6} (dB)	11,5	18,5
Receiver Threshold at BER = 10^{-6} (dBm)[4]	-84	-76
System Gain D' - D (dB)	114	106
CS antenna 90º bore-sight gain (dB)	16	16
CS azimuth and elevation radiation patterns	EN 302 085 [2]	EN 302 085 [2]
Terminal (TS) antenna boresight gain (dBi)[5]	16	16
TS antenna typical 3dB down half-angle Φ_3 (RPE type ≥ TS2 acc. to EN 302 085 [2])	10°	10°
NOTE: 3,5 GHz will be used as radio frequency throughout the calculations.		

NOTE 1: This channel spacing is considered the most representative for being carried over in the calculation. It is considered that the larger channel systems would lead the coexistence rules. Nevertheless lover spacing channels (e.g. from 1,5 MHz up), also widely popular, should more easily fit in that possible framework.

NOTE 2: CS and TS power are assumed equal for symmetric traffic. This value includes feeder losses for full indoor applications. The 35 dBm Maximum Power presently allowed in ETSI ENs (e.g. EN 301 021 [1] and 301 080 [16]) is considered not realistic from the co-existence point of view.

NOTE 3: The Noise Figure estimated from EN 301 021 [1] BER values and typical modulation formats would result in ~12 dB; however this seems too pessimistic and a value of 8 dB has been assumed, it should already give enough margin for the possible necessity of a selective RF channel filter of reduced size for TS.

NOTE 4: This value includes feeder losses for full indoor applications.

NOTE 5: A moderate antenna gain is used for Terminal Stations (TS), considered as a reasonable trade-off between cell coverage (which is not a so critical factor as at higher frequencies) and a small/cheap TS version.

Annex B: Simulation tool used in coexistence calculations for mesh systems using omnidirectional antennas

SEAMCAT (Spectrum Engineering Advanced Monte-Carlo Analysis Tool) is the implementation of a Monte-Carlo Radio simulation model developed by the group of CEPT Administrations, ETSI members and international scientific bodies. SEAMCAT is public object code software distributed by the CEPT European Radiocommunications Office (ERO), Copenhagen. The software packet itself and additional information are available in: "http://www.ero.dk/EROWEB/SEAMCAT/Seamcat.html."

The Monte-Carlo simulation method is based upon the principle of taking samples of random variables from their defined probability density functions (also called distributions). The user inputs distributions of possible values of the parameters, and the software uses them to extract samples (also called trial or snapshot). Then, for each trial SEAMCAT calculates the strength of the interfering and the desired signal and stores them as arrays.

The software derives the probability of interference taking into account the quality of the receiver in a known environment, and the calculated signals.

The Monte Carlo method can address virtually all radio-interference scenarios, like e.g. sharing or compatibility studies. This flexibility is achieved by the way the system parameters are defined. Each random parameter (antenna pattern, radiated power, propagation path, etc.) is input as a statistical distribution function. It is therefore possible to model even very complex situations by relatively simple elementary functions.

Annex C: Carrier-to-noise plus interference considerations

An important parameter for the coexistence is the needed carrier-to-noise plus interference ratio. Typically in the mesh applications OFDM modulation is used together with effective error correction methods. As a reference WLAN type error correction can be assumed. BER as a function of E_b/N_0 is for various data rates in AWGN for a constraint length 7 convolutional code is given in figure C.1 [12].

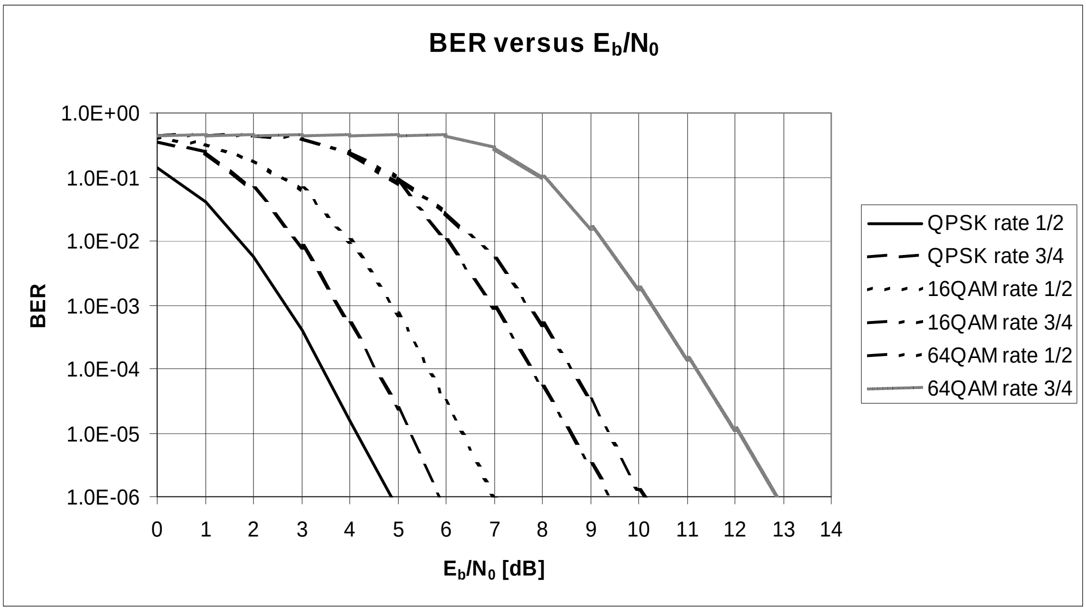


Fig C.1: BER vs. E_b/N_0 in AWGN channel for a constraint length 7 convolutional code.

Based on that, the BER as a function of input signal-to-noise ratio SNR_i can be calculated. The relation between the E_b/N_0 and SNR_i is:

$$SNR_i = \frac{E_b}{N_0} \cdot \frac{1}{BT_s} = \frac{E_b}{N_0} \cdot \frac{bN_s r}{BT_s}$$

where E_b = bit energy

N_0 = noise density;

B = noise bandwidth;

T_s = symbol duration;

b = number of coded bits per subcarrier;

N_s = number of subcarriers;

r = coding rate.

Using typical OFDM parameters the SNR_i can now be tabulated. The difference vs. E_b/N_0 for the abovementioned cases is –1,16, + 0,6, 1,85, 3,61, 3,61 and 5,37 dB. A new figure showing the BER as a function of SNR_i is shown in figure C.2.

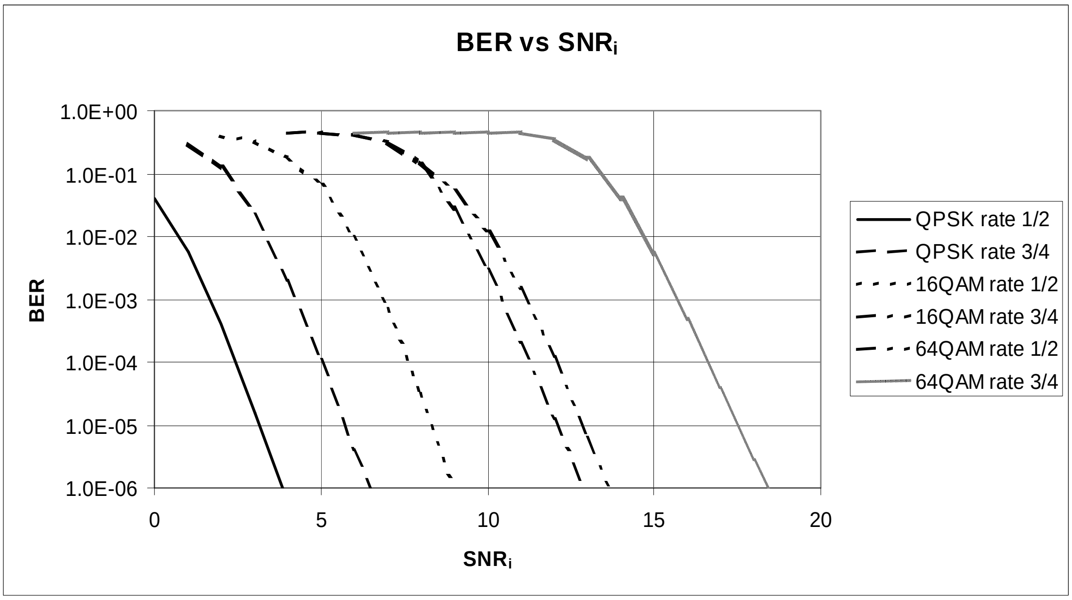


Figure C.2: BER vs. SNR_i in AWGN channel for a constraint length 7 convolutional code

Now the C/(N+I) criterion for the various modulation methods (QPSK, 16 QAM, 64 QAM) under OFDM can be evaluated. From the figure C.2 it can be seen that proper C/(N+I) criterions are those given in following table.

Table C.1: SNR limits for coded OFDM-modulations:

Modulation	C/(I+N) criteria for BER = 10^{-6} (implementation margin 0 dB)	C/(I+N) for BER = 10^{-6} from [14] with 5 dB implementation margin
QPSK rate 1/2	3,9 dB	9,4
QPSK rate 3/4	6,4 dB	11,2
16 QAM rate1/2	9,1 dB	16,4
16 QAM rate 3/4	12,7 dB	18,2
64 QAM rate 1/2	13,6 dB	(cr = 2/3) 22,7
64 QAM rate 3/4	18,4 dB	24,4

These values are remarkably lower than C/(I+N) criterias for corresponding uncoded single carrier modulations, which are 13,5 dB, 20,5 dB and 26,5 dB for BER of 10^{-6} and modulation QPSK, 16 QAM and 64 QAM, respectively.

History

Document history		
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