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Enhancement of the report with further elements relative to WiFi capacity			28 Oct. 08

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SUMMARY

In this document, we present a study on the capacity and architecture of the different systems that can be deployed in emerging countries. We namely consider WiMAX, HSDPA, 1x EV-DO, EDGE and WiFi. As several technological implementations are possible (bandwidth size equal to 1.25/5/7/10 MHZ, frequency of 450/900/2000/2600/3500 MHz), and several environments are to be studied (urban/rural) with a possible usage of an outdoor CPE, we perform a study on the coverage and throughput in different configurations and come out with general conclusions concerning the comparative capacity, coverage and architecture of the studied systems.

The conclusions drawn from this work are as follows:

- Coverage analysis: As expected, the coverage is extremely related to the frequency. The coverage of EV-DO 450 is thus the largest, far ahead of HSDPA 900 that, in turn, has a larger coverage than HSDPA 2000. On the other hand, having an outdoor CPE with a gain of 6 dB will increase significantly the coverage of all systems, but will increase also the costs. Outdoor CPE are thus to be used only when there are some far isolated users or when we have channels on high frequencies (e.g. WiMAX at 3,5Ghz).

- Capacity analysis: When the cells are deployed based only on coverage criteria, systems like EVDO or HSDPA at 2Ghz will have very large cells and will not be able to serve a large number of subscribers. A joint capacity-coverage dimensioning is thus necessary. We consider two case studies. The first is when the telecommunications operator has an already deployed GSM network and wants to reuse the existing sites to offer the internet service. We thus give the capacity of the resulting network for the different systems. The other case is when the operator has a target penetration for its service and wants to know the best inter-site distance for each technology.

- Architecture comparison: For 3GPP/3GPP2 systems (EDGE, HSPA, CDMA 2000), there is no major difference for network Packet Switch (PS) architecture. The access network composed of Base Stations and Base Station Controllers and the core network composed of a GGSN, SGSN and HLR (MSC and PDSN for CDMA 2000). The migration from GPRS to Edge or from EDGE to HSPA (or from CDMA 2000 EVDO Rev 0 to Rev A) does not need an hardware upgrade of the PS core network if PS core network capacity still sufficient after migration (since data rate in the access network will increase). For WiMAX, it provides a very simple all IP architecture with few elements in the core network (only an AAA server with embedded DHCP function) reducing needed OPEX. It has to be noted that architecture evolution is toward reducing the number of nodes in the network (e.g. RNC in Node B for HSPA). As of WiFi mesh, the architecture is also very simple but standardization process is not finished and many proprietary solutions are implemented.

- Voice over IP support: For HSPA+, WiMAX and CDMA 2000 Rev A, QoS mechanisms and radio performances will allow deploying a VoIP service offering a high quality call. However for HSPA+, since no product will be available before 2009, VoIP quality should be assessed when available. For

HSPA, 2008 product does not implement all features needed to deploy a VoIP service with QoS. For EDGE, it will be not possible to offer a VoIP service since mouth to ear delay is too high in bad radio conditions.

STATE-OF-THE-ART ANALYSIS OF THE BROADBAND ACCESS AND INFRASTRUCTURE DOMAIN

1 SCOPE OF THE STUDY

This document deals with the following technologies: WiMAX, HSDPA, 1x EV-DO, EDGE and WiFi.

2 INTRODUCTION

With the multiplication of standards and technologies, designing a new network in emerging countries is becoming a challenging task. The goal is to minimize costs while guaranteeing a good QoS. This document presents a general study that compares the capacity of the different systems, namely HSDPA, CDMA 2000 1xEVDO and WiMAX. These systems use different radio access technologies and can be deployed on different channels and frequencies. The following table gives the summary of the frequencies at which each technology can be deployed.

Table 1: Frequency with associated channel bandwidth

	Frequencies	Associated channel bandwidth	Licensed band?	Access Technology
HSPA	900Mhz, 2Ghz	5Mhz	YES	CDMA/TDMA
Edge	900Mhz, 1,8Ghz	200KHz	YES	TDMA
CDMA 2000 1x EV-DO	450Mhz, 800Mhz	1.25Mhz	YES	CDMA/TDMA
WiMAX	700Mhz, 2.5Ghz	5 or 10Mhz	YES	OFDMA
	3.5Ghz	5, 7 or 10Mhz	YES	OFDMA
WiFi/WiFi mesh	2.4Ghz, 5Ghz	20Mhz	NO	CSMA/CA

This document investigates several cases. First, if the telecommunications operator has a complete choice in terms of spectrum and technology, we compare the coverage, capacity and architecture of the candidate systems in the different environments to allow an optimal choice. In the case where the operator has already acquired a licence, the document aims at presenting a methodology for choosing the best inter-site distance for achieving a good QoS at low costs. Reusing existing GSM sites is also a studied option.

This document is organized as follows. In Section 3, we perform an analysis based on link budget to assess the throughput of HSDPA, CDMA 2000 1xEVDO and WiMAX. The main results are in terms of maximal cell range and corresponding throughput versus distance to the base station. In section 4, the methodology (and results) presented in section 3 is used to evaluate the capacities of the candidate systems in three cases: when the cells are coverage-limited, when reusing existing GSM sites, or when deploying a new, capacity-limited network. Section 5 is a comparative study about the support of voice over IP in the different systems. Section 6 compares the architectures of the candidate systems; this comparison is necessary to compare the CAPEX and OPEX needed when deploying the network. Section 7 eventually concludes the deliverable.

3 LINK BUDGET COMPARISON

The link budget methodology is summarised in Figure 1. The UL link budget is realized for one mobile located at cell edge transmitting at maximum power. It is performed for a given target edge UL data rate at a specific BLER target (usually 1%). One important assumption for the UL link budget is the noise rise level at the base station. The commonly used assumption is an UL load of 50%. Taking into account these assumptions, the signal to noise ratio at cell edge must be superior to the target SNR value. The maximum allowable path loss (MAPL) is then determined using the base station power and sensitivity, in addition to all gains and losses (BS antenna gain, diversity gain, handover gain, feeder loss, shadowing margin, penetration margin, ..). Finally, the UL maximum cell range is deduced based on an appropriate propagation model.

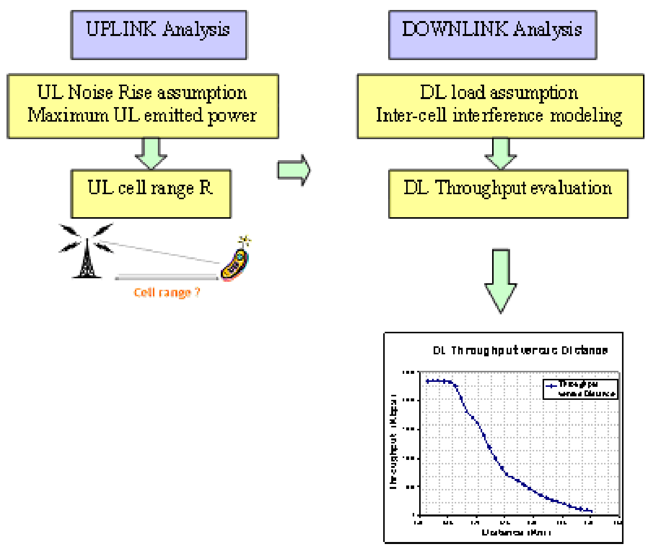


Figure 1: Link budget methodology [6].

For the DL, the analysis can not be performed in a linear manner as the interference amount depends on the mobile position in the cell. Depending on each system and based on a given DL load assumption, a system specific interference modelling is realized in order to determine the DL throughput expression as a function of the distance to the base station. For each load in the interfering cells, a curve distance to the base station/throughput is thus obtained. Note that this DL throughput is the peak rate, supposing that the user is alone in the cell and takes all the available power. The multi-user analysis, based on this peak data rate, is presented in Section 4.

Note:
The above described methodology (verifying uplink coverage before setting up downlink throughputs) has been fully done in this analysis for WiMAX, as we have link budgets for both uplink and downlink. However, for HSDPA, the uplink verification was done only for the 2 GHz spectrum, as we do not have a link budget for the 900 MHz bandwidth. For HSDPA 900 and CDMA 2000 1x EV DO at 450MHz, the analysis is only based on downlink throughput. In addition to this, we do not have simulation-based link level curves for EVDO as for the other systems; our analysis is thus based on ideal, step-like link level curves.
The following table summarizes the common parameters for the link budgets, used for all systems unless different parameters are specified.

Table 2: Common link budget parameters.

CPE SITUATION	INDOOR WINDOW/OUTDOOR
ENVIRONMENT TYPE	URBAN/RURAL
OUTDOOR CPE GAIN	6 dB
UL THROUGHPUT AT CELL EDGE	64 kbps
DL THROUGHPUT AT CELL EDGE	200 kbps
LINK LEVEL INPUTS	Cat 8 Va3 LMMSE
PROPAGATION MODEL	Cost-231 Hata
DL LOAD OF SERVING CELL	100%
DL LOAD OF INTERFERING CELLS	0-100%
MIMO SCHEME	SISO
NODE B TOTAL POWER	43 dBm
COVERAGE PROBABILITY	90%
MAST HEAD AMPLIFIER	used
SCHEDULER	Round robin
INTER SITE DISTANCE	1.5 cell range
BTS ANTENNA GAIN	17 dBi
FEEDER LOSS	3 dB
THERMAL NOISE	-173.83 dBm/Hz
UE MAXIMAL POWER	21 dBm

3.1 HSPA

3.1.1 Parameters

The same parameters as in Table 2 are used. The uplink link budget is used in HDPA 2000 to verify that the UL coverage is achieved at cell edge. For HSPA 900, we do not have a validated link budget for HSUPA 900 to perform this verification.

Recall that, in HSDPA, there is no intra-cell interference between users, but only between users and the common channels. The overall proportion of HSDPA common channels in the power budget is equal to 20%.

3.1.2 Results

3.1.2.1 HSDPA 900

Figure 2 to Figure 5 plot the HSDPA 900 peak throughput versus distance to base station for different CPE situations (outdoor/indoor Window) and for urban and rural areas. Three curves are given for each case: one for an isolated cell (0% load), another for a load of 50% in the adjacent cells and the third for a fully loaded system.

The first, and most intuitive, observation to make is that rural coverage is better that urban coverage as the propagation is better (the cell may reach a range of 51 Km in rural areas compared to a maximum of 12 Km in urban areas, with a cell edge DL throughput of 200 Kbits/sec).

Second, using an outdoor CPE increases the coverage because of the lower attenuation. For example, in urban areas, the maximal cell range is of 5 Km when putting the CPE indoor, while a 12 Km range can be attained for outdoor CPE. So, if the aim is to serve more users with less site density, an outdoor CPE is necessary.

Third, Figure 2 to Figure 5 represent the throughput for three different load situations at neighbouring cells. We can observe that the influence of inter-cell interference is small as we are in large cells where we are limited by noise and not interference at cell edge.

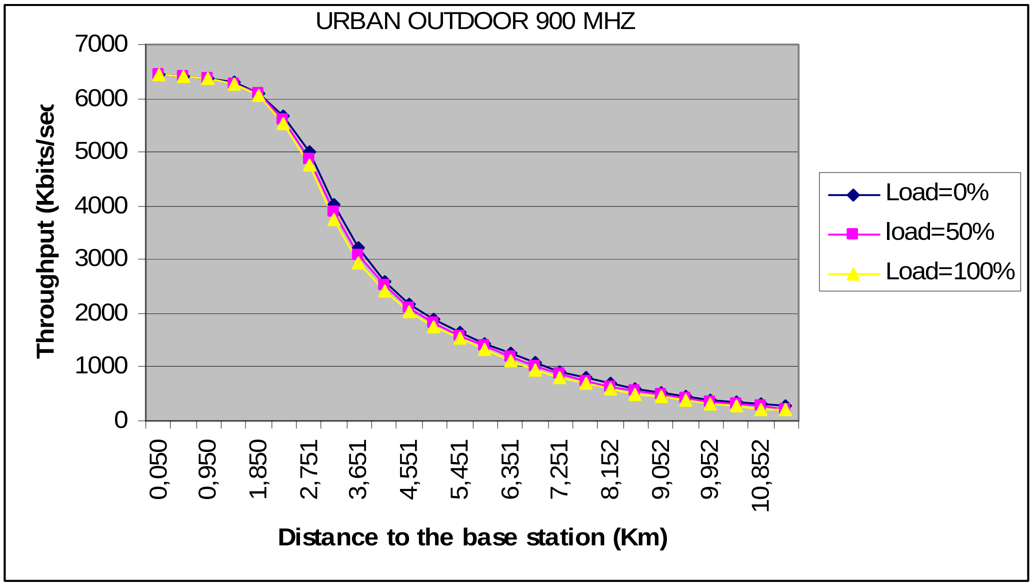


Figure 2: HSDPA900 throughput vs distance to BS for outdoor CPE in urban areas.

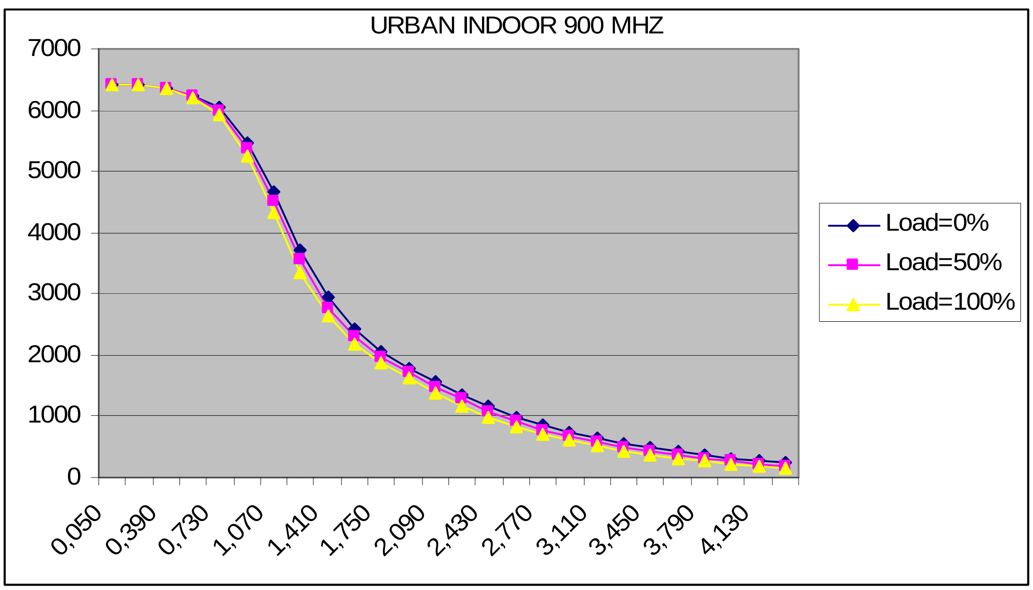


Figure 3: HSDPA900 throughput vs distance to BS for indoor CPE in urban areas.

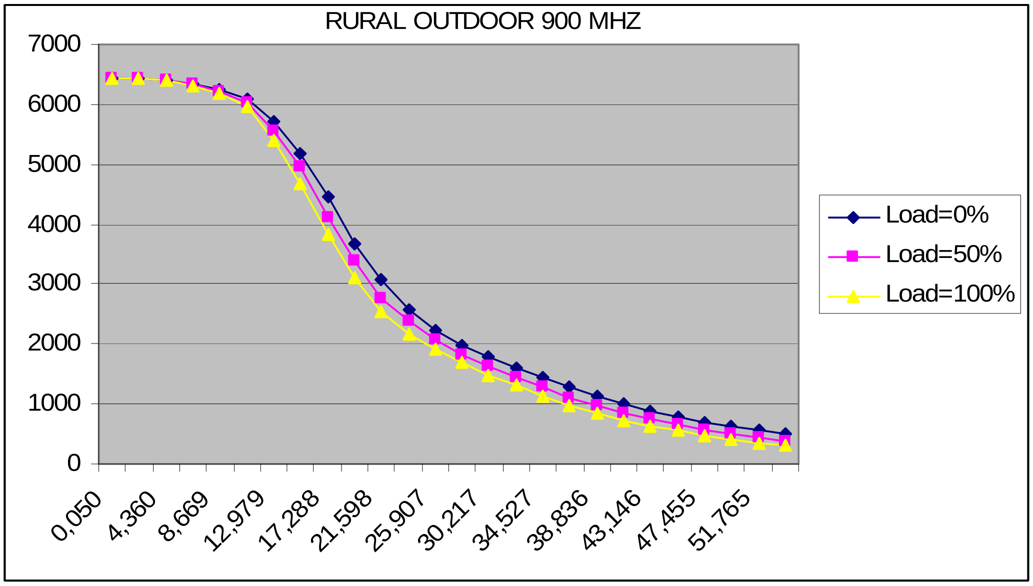


Figure 4: HSDPA900 throughput vs distance toBS for outdoor CPE in rural areas.

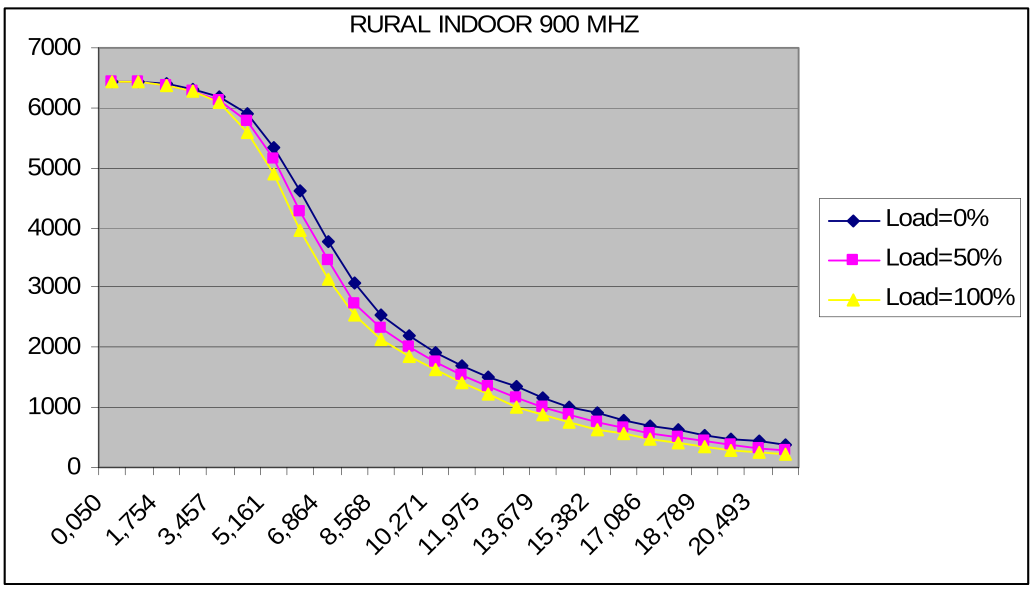


Figure 5: HSDPA900 throughput vs distance to BS for indoor CPE in rural areas.

The following table summarizes the cell range for the different situations for HSDPA 900.

Table 3: HSDPA 900 cell ranges.

	Indoor CPE	Outdoor CPE
Urban	4.3 Km	11.3 Km
rural	21.4 Km	53.9 Km

3.1.2.2 HSDPA 2000

Figure 6 to Figure 9 show the throughput for HSDPA 2000. The conclusions are the same as for HSDPA 900 concerning the impact of outdoor CPE and the difference between urban and rural areas. However, the cell range is smaller than in the 900 MHz bandwidth as the propagation conditions are more difficult (6 Km for urban outdoor compared to 12 Km for the HSDPA 900 case).

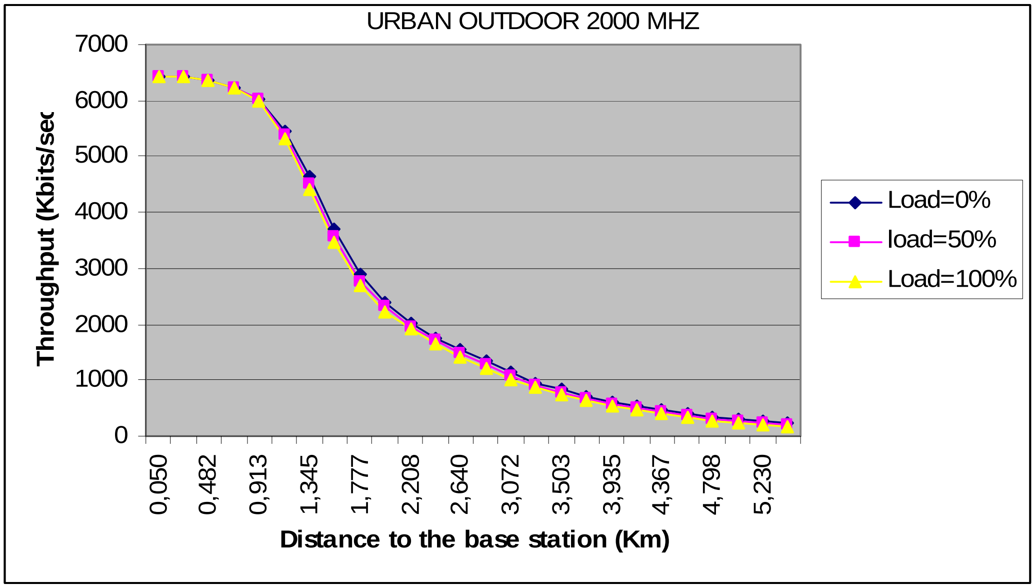


Figure 6: HSDPA2000 throughput vs distance to BS for outdoor CPE in urban areas.

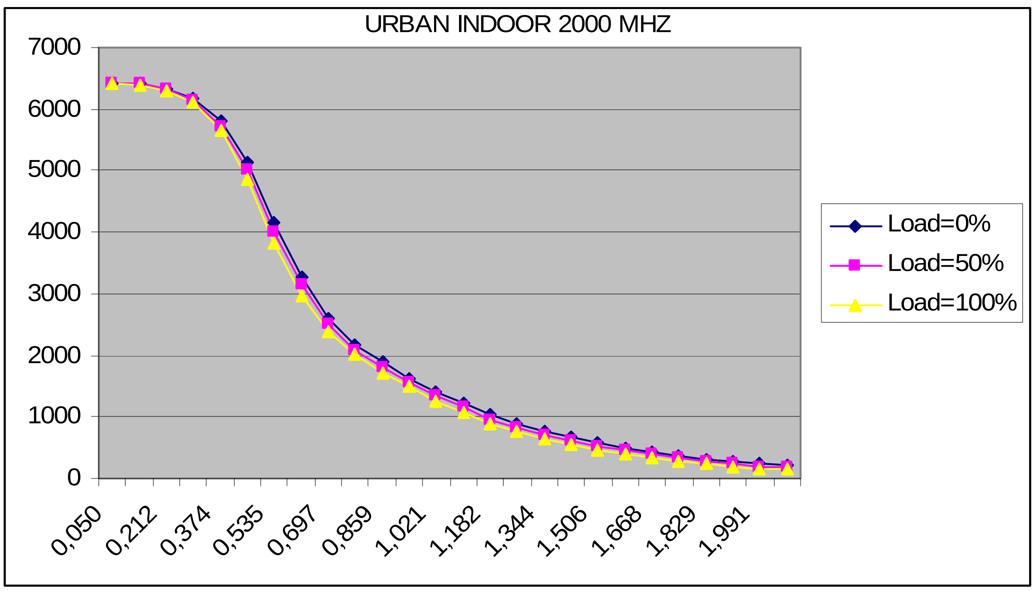


Figure 7: HSDPA2000 throughput vs distance to BS for indoor CPE in urban areas.

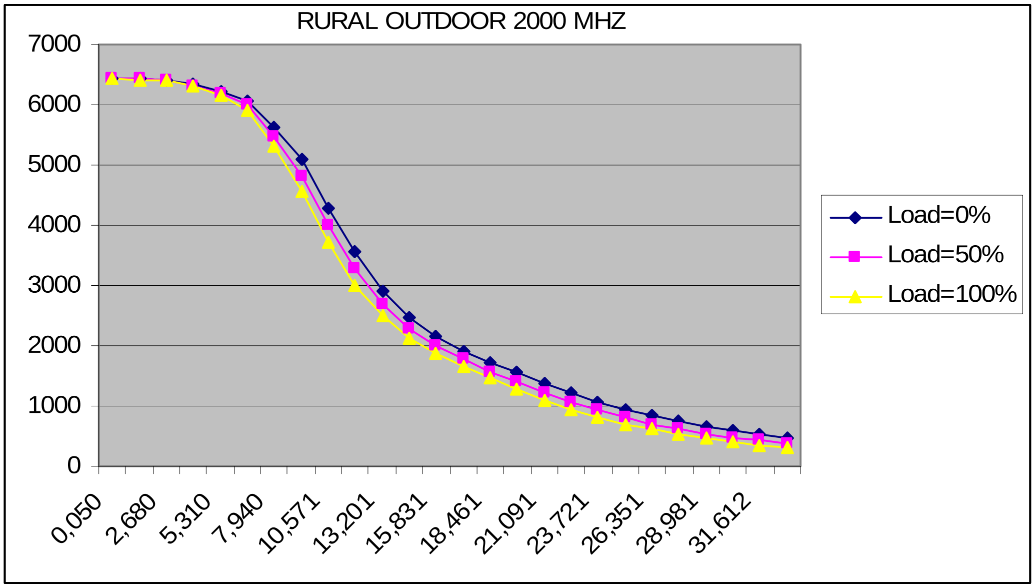


Figure 8: HSDPA2000 throughput vs distance to BS for outdoor CPE in rural areas.

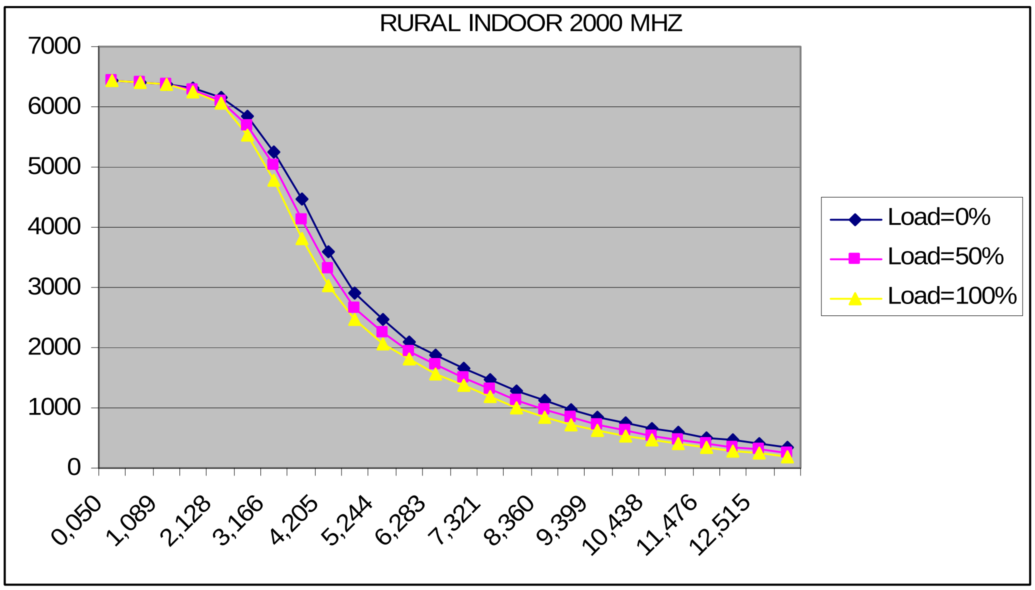


Figure 9: HSDPA2000 throughput vs distance to BS for indoor CPE in rural areas.

The following table summarizes the cell range for the different situations for HSDPA 2000.

Table 4: HSDPA 2000 cell ranges.

	Indoor CPE	**Outdoor CPE**
Urban	2 Km	5.4 Km
Rural	13 Km	32.9 Km

3.2 WiMAX

3.2.1 Parameters

For WiMAX, in addition to the common parameters specified above, we consider the following specific parameters:

Table 5: WiMAX link budget parameters.

FREQUENCY	2600 MHZ/3500 MHZ
FREQUENCY REUSE MODE	Reuse 3
DL/UL TDD RATIO	2
MIMO SCHEME	Rx diversity
DL MODE	FUSC
UL MODE	PUSC
BANDWIDTH	5/7/10 Mhz

We recall that the link budget is based on an analytical evaluation of the number of collisions, leading to different values of the SINR, as described in [6]. The link level curves are then used to obtain corresponding peak throughputs, that are then averaged based on the collision probabilities.

3.2.2 Results

3.2.2.1 WiMAX at 2600 MHZ

When assessing the throughput of WiMAX, we obtain the same observations as for HSDPA concerning the impact of using outdoor CPE (an increase in cell range) or the fact that cells in rural environments are larger. So, in this section, we will focus on a specificity of WiMAX of allowing a flexible carrier size (5, 7 or 10 MHz). Figure 10 to Figure 11 and Figure 12 to Figure 13 show that using a larger bandwidth will increase the throughput, even if the base station power is the same. This is because the number of resource blocks increases (doubles), and even if each resource block has less power, the overall throughput increases as the inter-cell interference will be reduced by the same manner.

Comparing now WiMAX 2600 with HSDPA 900 and HSDPA 2000, the cell range is smaller because the propagation conditions are worse. In addition to that, we can see that WiMAX is more sensitive to inter-cell interference even if a reuse 3 is used because there is no scrambling between the different cells to decrease the impact of interference. The impact of interference is even larger when using an outdoor CPE because inter-cell interference will be much larger than the thermal noise.

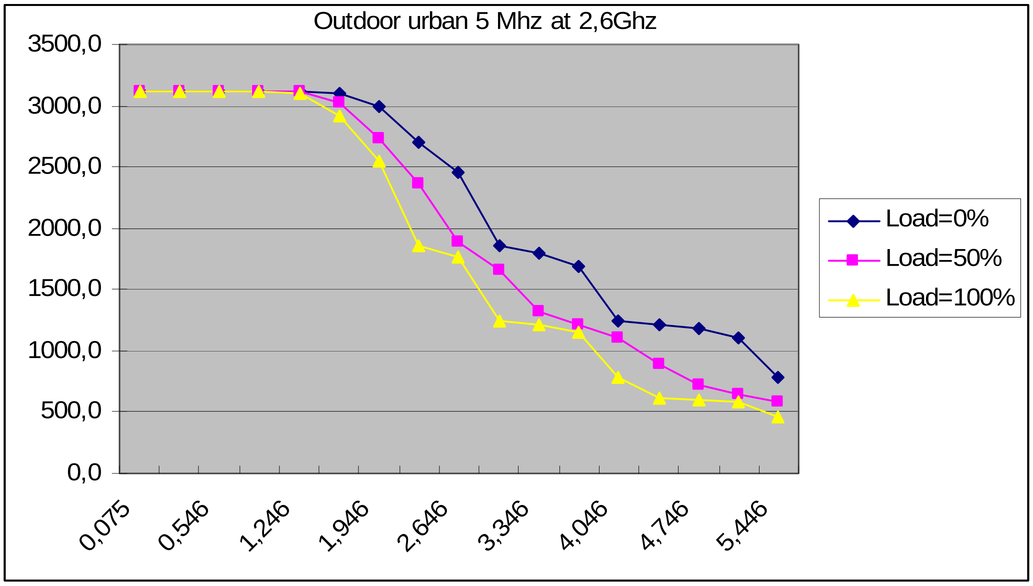


Figure 10: WiMAX 2600 throughput for outdoor CPE in urban areas, 5 MHz bandwidth.

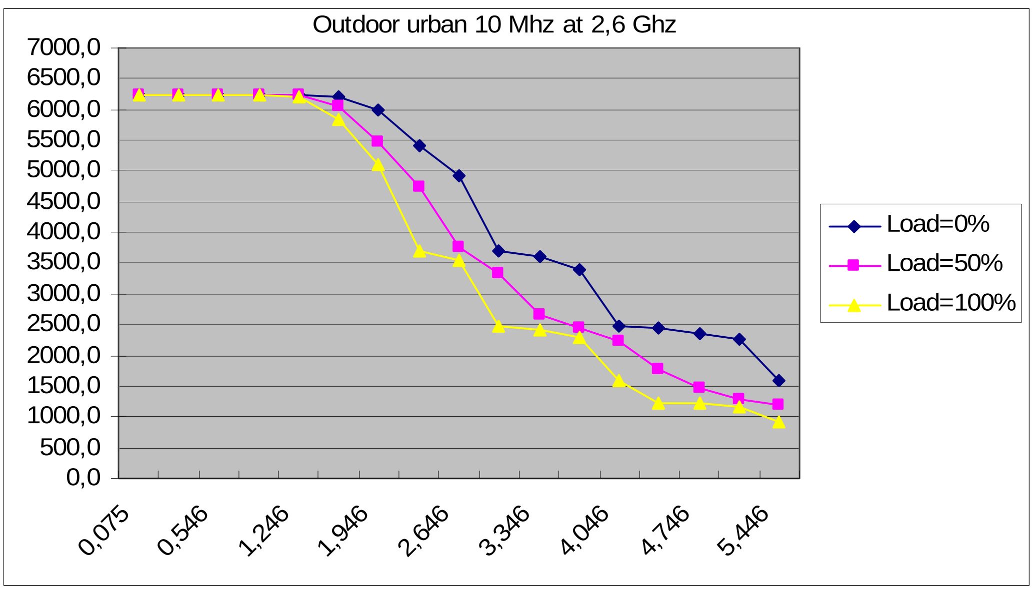


Figure 11: WiMAX 2600 throughput for outdoor CPE in urban areas, 10 MHz bandwidth.

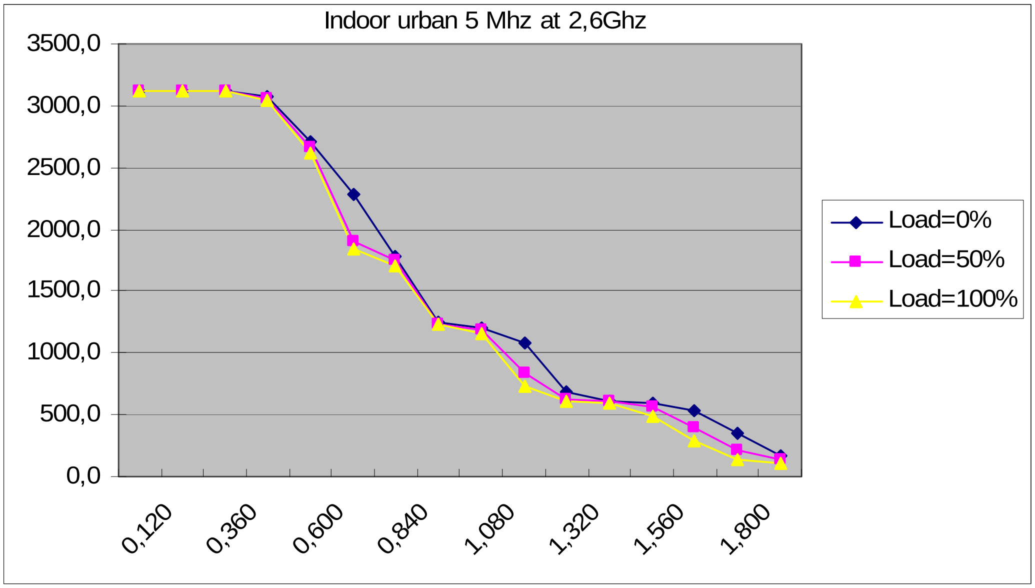


Figure 12: WiMAX 2600 throughput for indoor CPE in urban areas, 5 MHz bandwidth.

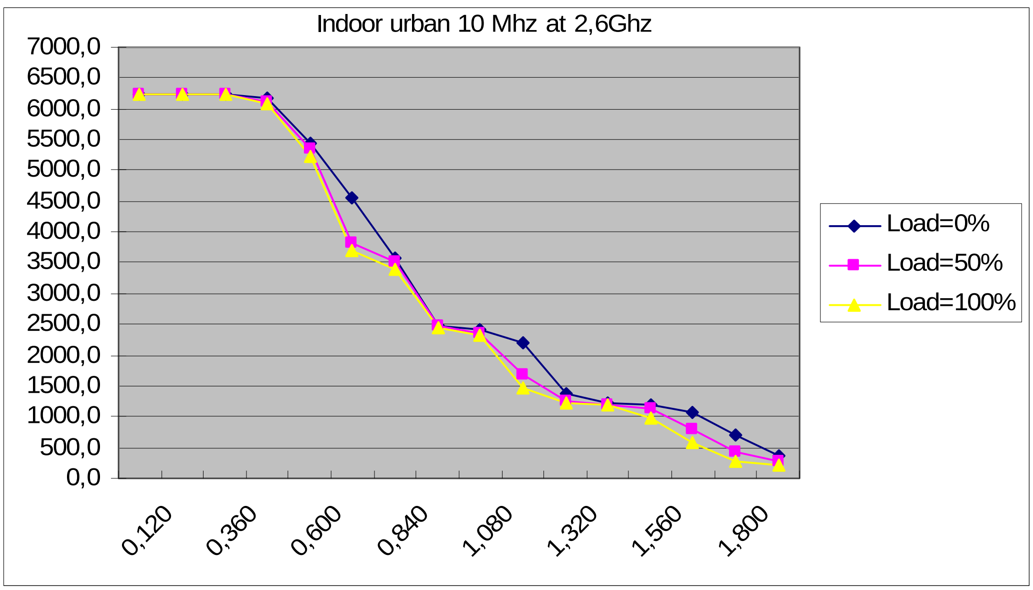


Figure 13: WiMAX 2600 throughput for indoor CPE in urban areas, 10 MHz bandwidth.

The following table summarizes the maximal cell range for the different situations for WiMAX 2600.

Table 6: WiMAX 2600 cell ranges.

	Indoor CPE	**Outdoor CPE**
Urban	1.8 Km	5.5 Km
Rural	3.2 Km	15 Km

3.2.2.2 WiMAX at 3500 MHZ

For the WiMAX 3500, the range is obviously the lowest, as illustrated by Figure 14. In addition to that, using a larger carrier will increase accordingly the throughput (Figure 15).

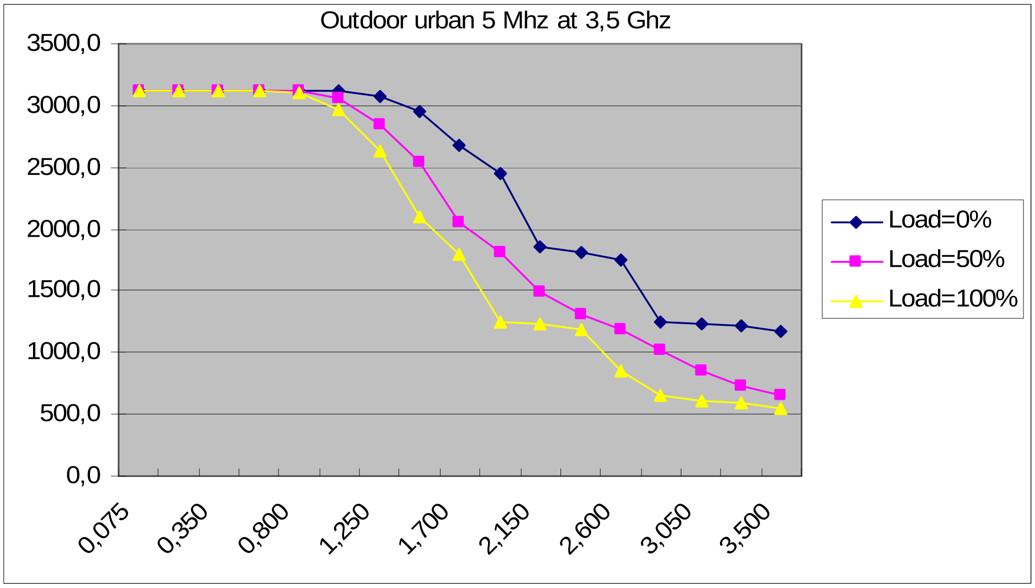


Figure 14: WiMAX 3500 throughput for outdoor CPE in urban areas, 5 MHz bandwidth.

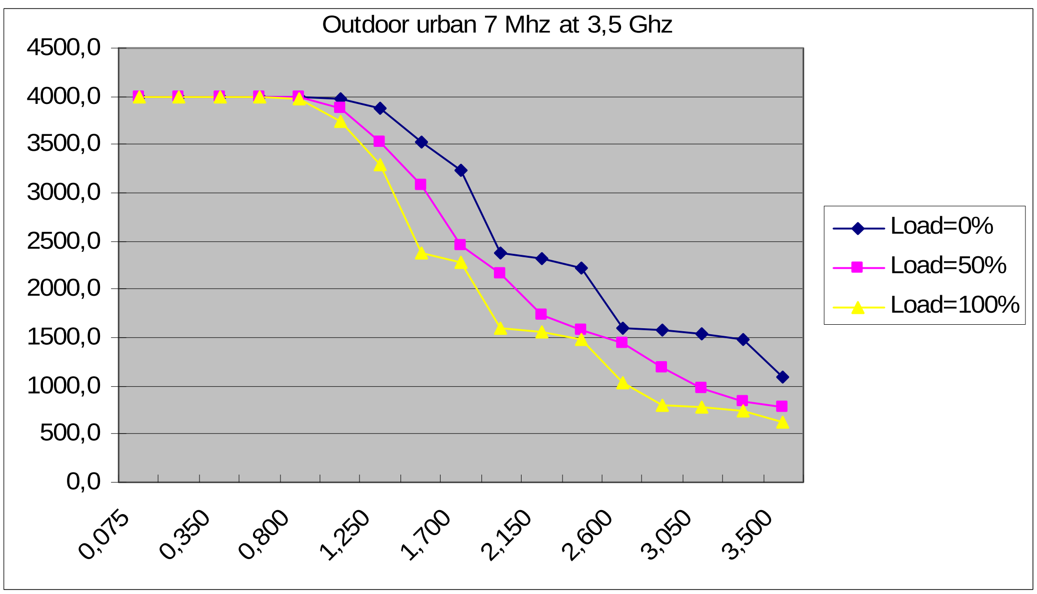


Figure 15: WiMAX 3500 throughput for outdoor CPE in urban areas, 7 MHz bandwidth.

The following table summarizes the cell range for the different situations for WiMAX 3500.

Table 7: WiMAX 3500 cell ranges.

	Indoor CPE	**Outdoor CPE**
Urban	1.2 Km	3.5 Km
Rural	2.2 Km	10 Km

3.3 CDMA 2000 1x EVDO

3.3.1 Parameters and hypotheses

In order to analyse the throughput for 1xEVDO, we use the HSDPA link budget 55] and implement the parameters and propagation models described in [2]. This is possible because of the large similarities between 1x EV DO and HSDPA, especially for using CDMA between different cells; The inter-cell interference analysis is thus the same. Note that, in EVDO, there is no CDMA use within the same cell, even with the common channels. We thus obtain the throughput without any common channels, and multiply it by the proportion of data transmission, taken equal to 75%.
The table below summarizes the additional parameters used for the EVDO link budget.

Table 8: CDMA 1x EVDO link budget parameters.

FREQUENCY	450 MHZ
ORTHOGONALITY FACTOR	0
COMMON CHANNELS TIME	25%
LINK LEVEL CURVES	Step functions
BANDWITH	1.25 MHz

3.3.2 Results

Figure 16 to Figure 19 show the throughput of EVDO systems in urban and rural areas. The first conclusion is that the cell ranges are huge, as the propagation is very good. However, the throughput near the base station is low compared to HSDPA and WiMAX as the peak data rate for EVDO is low (the bandwidth is equal to 1.25 MHz, to compare with the 5 MHz of HSDPA or WiMAX). Another point to take into account is the propagation delay for these large cells, making them unfeasible.

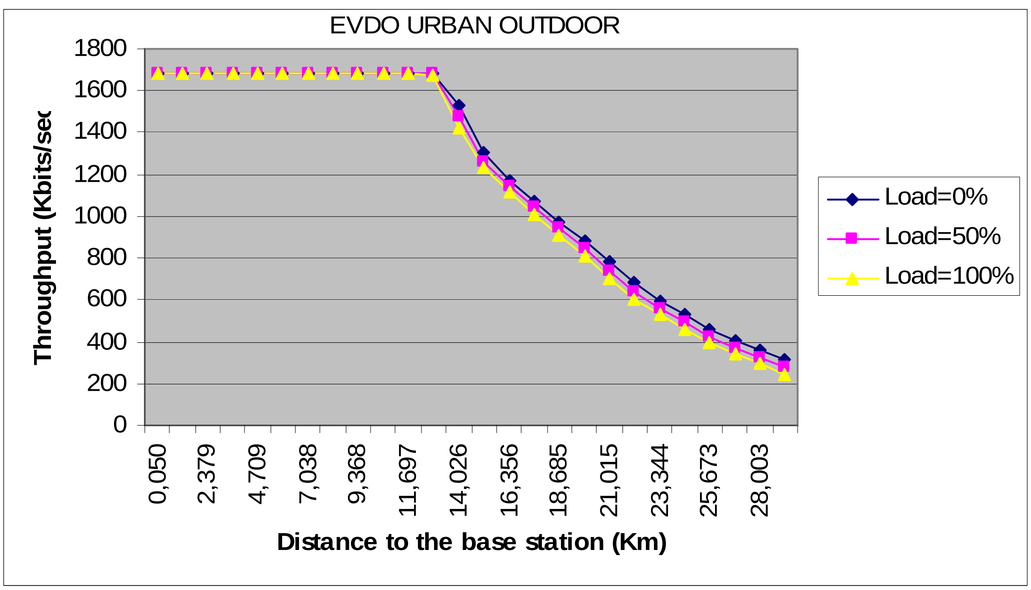


Figure 16: EVDO throughput for outdoor CPE in urban areas.

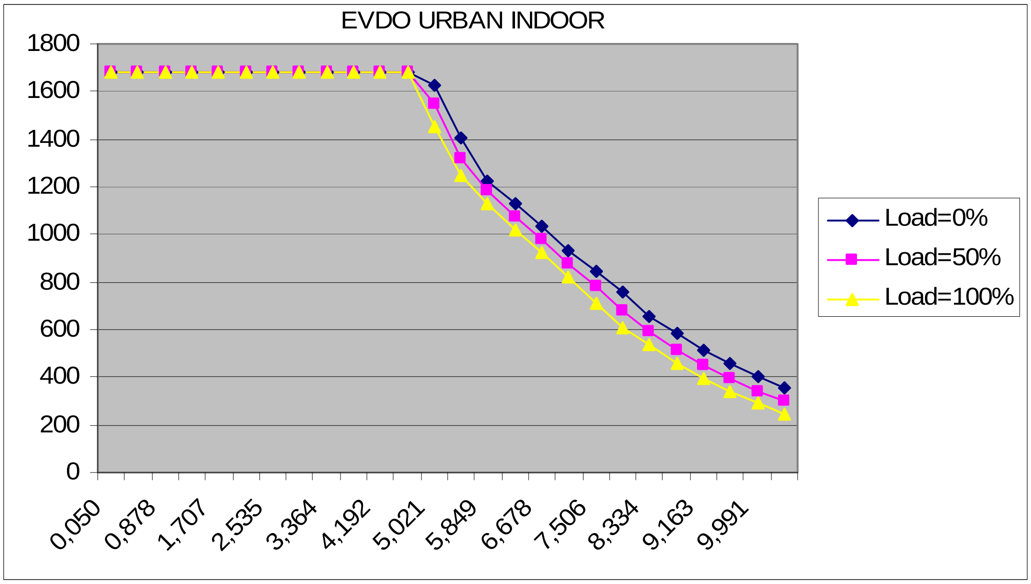


Figure 17: EVDO throughput for indoor CPE in urban areas.

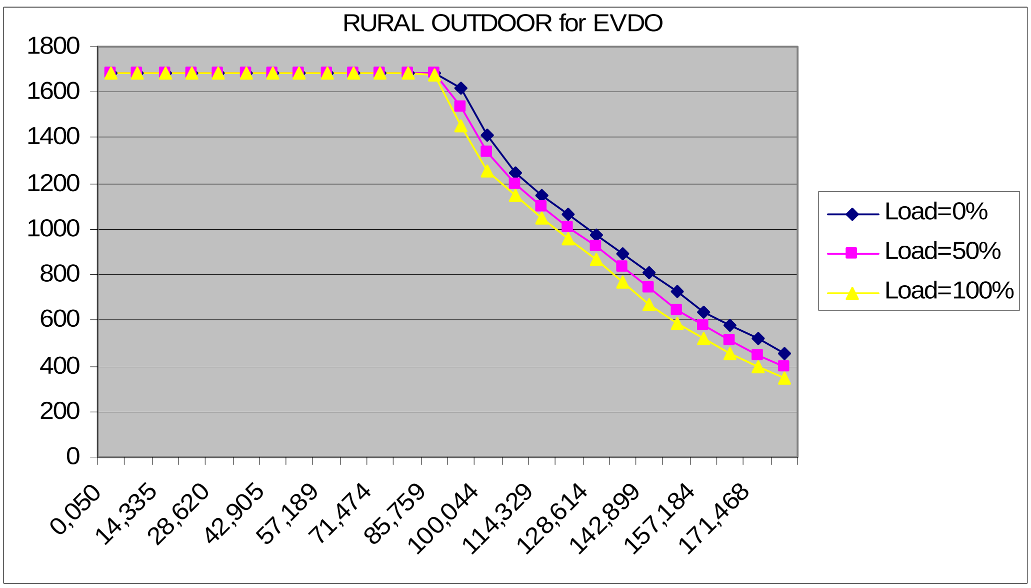


Figure 18: EVDO throughput for outdoor CPE in rural areas.

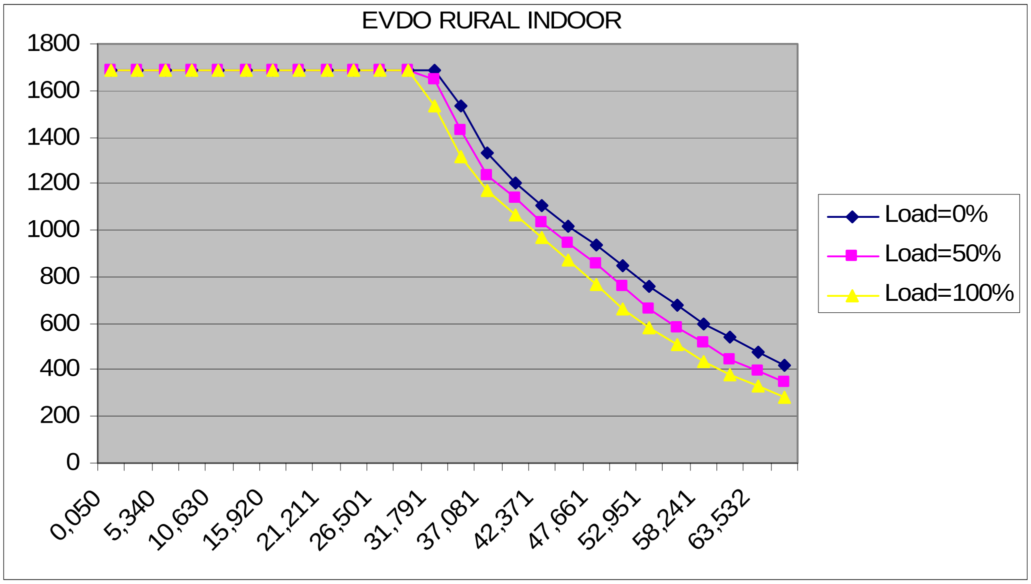


Figure 19: EVDO throughput for indoor CPE in rural areas.

The following table summarizes the maximal cell range for the different situations for EVDO.

Table 9: EVDO cell ranges.

	Indoor CPE	**Outdoor CPE**
Urban	10 Km	29 Km
rural	66 Km	178 Km

4 CAPACITY EVALUATION

In order to compare the capacity of the different proposed systems, we need to construct functions that give, known the traffic offered to each system, the QoS indicators. To analyse the flow level capacity of a given network, i.e. the steady-state distribution of the number of users in the cell, we need to take into account the traffic characteristics in addition to the end-user throughput, obtained from link budget studies. Considering FTP-like elastic calls, where a mobile stays in the network while downloading a file of size *Z* Kbits, the download time will depend on the throughput, itself depending not only on the number of users, but also on the number of users having the different radio conditions. We will study all this in details in the following.

4.1 Cellular systems capacity analysis

4.1.1 HSDPA capacity analysis

In HSDPA, resources are shared between users making one user having a proportion of the peak throughput available in its position. As we consider here elastic calls, a processor sharing model is adequate. However, the achieved throughput for the same emitted power decreases when the user moves towards the cell edge. We thus divide the cell into n zones, creating n classes of data calls that share the resources as in [3]. The values of throughput versus the cell distance are obtained using the link budget tool as shown in the previous section. The details of the processor sharing analysis are given in [4].

4.1.2 WiMAX capacity analysis methodology

Although WiMAX does not implement power control like 3G but it uses adaptive modulation and coding in order to adapt throughput to the conditions of propagation and interference. The result is that cell-edge users will use more resources than those at cell centre if they want to achieve the same throughput.

We use the same division into rings and the analytical model developed in [5] and implemented in the link budget tool [6]. The capacity will be shared by non-guaranteed-bit rate data users in the n zones. The capacity values are obtained using the link budget. The link budget gives the throughput of one user if allocated all the resources, at the different positions of the cell. The processor sharing algorithm can be applied considering that the resources (subchannels) are shared equally among users.

4.1.3 CDMA 1x EV-DO hypothesis

CDMA 1x EV-DO is an HSDPA like system and capacity (power) is shared among users. A processor sharing model is thus adequate, similar to HSDPA. The values of throughput versus the cell distance can be obtained by modifying the link budget tool for the 450 MHz carrier.

4.1.4 Load calculation methodology

In cellular systems, inter-cell interference plays a major role and has a large impact on the capacity of the target cell. In HSDPA and CDMA 1x EV-DO, inter-cell interference decreases the peak throughput that can be achieved at each position of the cell. In WiMAX, it decreases the throughput of each subchannel and thus the required number of subchannels to achieve a given throughput increases.

We propose, as in [3], an iterative algorithm to calculate the load in the interfering cells and use it in the target one:

1. Let the load of interfering cells be equal to an initial value of 0.5 for example.
2. Evaluate the required capacity in each zone using the given value of load in interfering cells.
3. Evaluate the average load in the target cell, knowing the distribution of the number of users calculated in stage 2.
4. Compare the calculated load to the initial load. If there is a significant difference, make the load of interfering cells equal to the calculated load and repeat iterations 2-4 until convergence.

4.2 Capacity evaluation: focus on WiFi

4.2.1 Throughput at the access level

- Throughput of an isolated WiFi cell

WiFi packet level throughput has been studied in several works. The throughput for permanent TCP flows has been performed by Lebeugle and Proutiere [18]. Their model is easily applied to the access level of an isolated WiFi cell. The throughput of one subscriber is given by:

$$T_{access}(\vec{x}) = \frac{\varphi_{access}(\vec{x})}{x}$$

(equation a)

where $\vec{x}$ = (x_1, …, x_i,…, x_J) is the number of users belonging to each class of throughput in the cell at a given time, and $\varphi_{access}(\vec{x})$ is the global throughput that can be achieved by the cell, for a number of active clients represented by x.

- Impact of inter-cell interference

In the presence of several cells, inter-cell interference has a large impact as collisions will occur not only between users of the same cell, but also from users in interfering cells. An RTS/CTS scheme is thus necessary to avoid these collisions, especially from hidden nodes (non-interfering stations but in the range of transmission of a common third station). In this scheme, a station, before beginning its transmission, sends a frame called Ready To Send (RTS) and waits for receiving a Clear To Send (CTS) frame from its peer. This creates exclusion regions in the interfering cells where any transmission will block all other users in the two cells.

Knowing the large impact of interference on the system, a good WiFi network deployment must implement a reuse 3 scheme to avoid using the same frequency in adjacent cells. In fact, if adjacent cells use the same channel, large parts of them will enter in the exclusion region, degrading thus severely the performance. In particular, if the base stations are in interference range each others, the whole cells are considered as exclusion regions, as shown in Figure 20-a. However, even with reuse 3, some parts of the cells in the second ring will still enter in the exclusion regions, as users at cell edges still interfere, as shown in Figure 20-b.

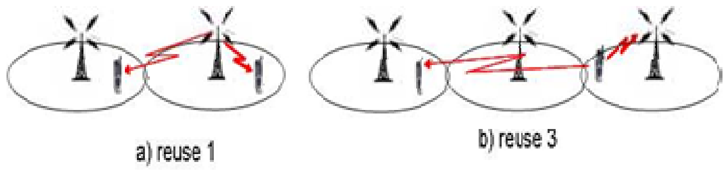


Figure 20: Interference in WiFi networks.

Considering this interference, the vector $\vec{x}$ is no more sufficient to obtain the throughput of the cell as in equation a; we must also know the number of users in the exclusion regions of interfering cells. Denote by $\vec{x}_{exc}$ this vector, with $x_{exc,i}$ the number of users of class *i* in the interfering cells that enter in the exclusion region of the target cell. The average throughput achieved at the target cell is thus:

$$\varphi_{access}(\vec{x}) = \sum_{x_{exc}} [\varphi_{access}(\vec{x} + \vec{x}_{exc}) \Pr[\vec{x}_{exc}]]$$

(equation b)

The probability distribution of the number of users in the exclusion region depends on the distributions of the number of users in the adjacent cells. This distribution cannot be obtained based on a packet level analysis like the one described in this section. We will show how to derive this distribution using a fixed point flow level analysis in §4.2.3. We will explain here how to calculate the distribution of $\vec{x}_{exc}$ knowing the distribution $\Pr[\vec{x}]$ of the number of users in a typical cell of the network (homogeneous regular setting).

Let us first note that only cell edge users enter the exclusion region when using a reuse 3 scheme, and these users usually have the lowest transmission rate; $\vec{x}_{exc}$ can thus be reduced to one random variable x_{exc}. Let ξ be the proportion of cell edge users in a given cell of the network that interfere with the target cell. If there are $x_j^{(k)}$ cell edge users in cell k, the number $x_{exc}^{(k)}$ of users in cell k entering in the exclusion region of the target cell has a binomial distribution. Conditioning on $x_j^{(k)}$, we have the probabilities:

$$\Pr[x_{exc}^{(k)} = z] = \sum_{x_j^{(k)}} \binom{x_j^{(k)}}{z} \xi^z (1-\xi)^{x_j^{(k)}-z} \Pr[x_k = x_j^{(k)}]$$

(equation c)

The random variable x_{exc} is thus the sum of the i.i.d variables $x_{exc}^{(k)}$ over the different interfering cells and deriving its distribution $\Pr[x_{exc}]$ is straightforward. This distribution is injected into equation (b) to obtain the throughput at access level.

4.2.2 Throughput at the backhaul

Knowing the throughput on the access is not sufficient in a WiFi network, as the backhaul may be a bottleneck. The throughput achieved by a user is thus the minimum between the throughputs at access and backhaul:

$$T(\vec{x}) = \min(T_{access}(\vec{x}), T_{back}(x))$$

(equation d)

The simplest deployment of WiFi networks is by connecting each access point to the Internet via a DSL connection. The backhaul throughput is thus constant (e.g. $\varphi_{dsl} = 512$ Kbps), and one user will share this throughput with the x − 1 other connected users and get:

$$T_{back}(\vec{x}) = \frac{\varphi_{dsl}}{\sum_{i=1}^{J} x_i}$$

(equation e)

where J is the number of classes of throughput in the cell.

However, this kind of deployment is too costly, especially in cities where the mobile operator does not have his own wired infrastructure. To solve this problem in a cost effective way, the DSL connections can be substituted by wireless ones, deploying thus hierarchical WiFi/WiMAX or WiFi mesh networks. The backhaul of WiFi Mesh networks is based on the IEEE 802.11a standard. We will consider the case of multiple radio interfaces on the backhaul: When choosing the radio interface for communicating with its neighbour, each AP can choose between eight non-overlapping channels (there are, in total, 12 non-overlapping channels, among them 8 channels can be used in outdoor situations).

Each access point that is not connected to the Internet will have a routing table that gives the best way to route packets. Before arriving to destination, information relative to a typical client are then routed within the network and are authorized to make several hops. In order to insure an acceptable performance, the network is designed so that a maximum of M hops is allowed, with M = 2 or 3. In this case, the throughput will be divided equally between the clients of the base station as well as the clients that will be routed from neighbouring backhaul nodes. We will consider, when deriving the throughput, that each WiFi cell has, in average, x connected clients. We will show in §4.2.3 how to calculate x based on a flow level analysis.

As the number of 802.11a channels is limited, they have to be reused at different APs when the number of hops is large. Before deriving the backhaul throughput, we have then to account for the impact of inter-AP interference on the throughput. Let us begin by considering only one link. At this link, there are only two base stations using the medium: one emitting packets and the other sending ACKs. However, there are also Y APs falling within the interfering range. Note that, in a regular setting, all the two-directional links between adjacent cells have the same range, leading to homogeneous radio conditions. The throughput of the backhaul link, in the absence of interference, is then given by $\varphi(x = 1)$.

In the presence of y active interfering APs, the throughput that can be achieved by the link is equal to $\varphi(1 + y)$. Knowing that an access point is active with probability r, the throughput is averaged over the different configurations by:

$$\varphi_{back}(Y) = \sum_{y=0}^{Y} \binom{Y}{y} r^{y} (1-r)^{Y-y} \frac{\varphi(1+y)}{1+y}$$

(equation f)

Note that, for M = 0, the system is equivalent to a hotspot WiFi network and each access point has to serve its own users only. The throughput will thus be given by equation (e).

For M > 0, a frequency planning is needed to optimize the usage of WiFi links over the network and reduce the inter-cell interference at the backhaul. Once the frequency reuse map is drawn, the backhaul throughput can be derived accordingly. We will show in the following how to derive the number of users to route for the M equal to 1 and 2, in a regular hexagonal setting. The proposed methodology can be used to derive the frequency reuse map in the other possible settings.

- Networks with a maximum of one hop:

For M = 1, a maximum of one hop is permitted. This is possible if the access points represented by red dots in Figure 21 have no connection to the Internet.

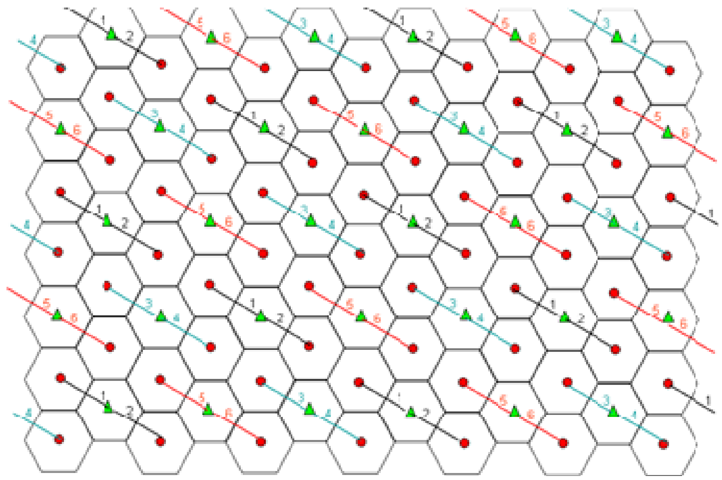


Figure 21: Regular WiFi mesh networks with a maximum of one hop permitted.

In this figure, we represent the backhaul links between APs by segments that are numbered between 1 and 8 (there are 8 non-overlapping 802.11a outdoor channels). It can be observed that each gateway (AP with Internet connection) will have to route the users of 2 neighbouring cells. Based on this observation, only 2 backhaul links are needed at each Internet gateway and a reuse 3 can be deployed, avoiding thus the problem of inter-cell interference at backhaul as the APs are too far to interfere. We can then distinguish between 2 classes of APs:

• For APs behaving as gateways, the average number of neighbouring cell users that they will serve is equal to $2\overline{x}$. The backhaul throughput for a user connected to a gateway is thus given by:

$$T^{1}_{back}(x) = \frac{\varphi_{dsl}}{x + 2\overline{x}}$$

• For an access point connected to the Internet via a WiFi mesh connection, we must take into account the WiFi as well as the wired connections:

$$T^{2}_{back}(x) = \min\left[\frac{\varphi_{dsl}}{x + 2\overline{x}}, \frac{\varphi_{back}(0)}{x}\right]$$

- <u>Networks with two possible hops:</u>

When the number of Internet connections is further reduced to allow a maximal number of two hops at the backhaul, a frequency planning is to be performed in order to reduce interference. We illustrate a possible solution in Figure 22, where only APs that are represented by green triangles behave as gateways, while the other have to route their packets via WiFi mesh connections. In this Figure, all the 8 non-overlapping channels will be used.

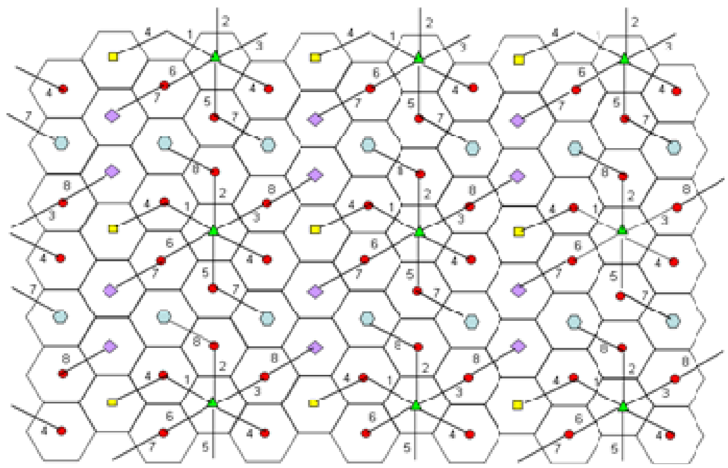


Figure 22: Regular WiFi mesh networks with a maximum of two hops permitted.

Again, we distinguish between four classes of APs:

• For gateways, the average number of other-cell users that will share the wired connection is equal to 11 $\bar{x}$, the backhaul throughput is thus given by:

$$T_{back}^{1}\ (x)=\frac{\varphi_{dsl}}{x+11\bar{x}}$$

• For APs with only one hop that are not used as mesh routers (one fifth of the red dots, connected to the gateway with the channel 4), they will not have to route any additional users, but they are subject to inter-cell interference from two neighboring access points using the same channel. The backhaul throughput $\varphi_{back}(2)$ is calculated as in equation (f). The overall backhaul throughput is thus given by:

$$T_{back}^{2}(x)=\min[\frac{\varphi_{dsl}}{x+11\bar{x}},\frac{\varphi_{back}(2)}{x}]$$

• For APs with one hop used as mesh routers (the other red dots in Figure 3), they are not subject to interference but have to route the packets belonging to users in adjacent cells. Knowing that the 802.11a throughput is equal to $\varphi_{back}(0)$, calculated as in equation (f), the backhaul throughputs is given by:

$$T_{back}^{3}(x)=\min[\frac{\varphi_{dsl}}{x+11\bar{x}},\frac{\varphi_{back}(0)}{x+\bar{x}}]$$

• For the other APs, they have two hops until attaining the Internet gateway: the first hop is interfered by two APs and has the throughput $\varphi_{back}(2)$, while the second hop is not subject to interference and has the throughput $\varphi_{back}(0)$. The resulting backhaul throughput is thus:

$$T_{back}^{4}(x)=\min[\frac{\varphi_{dsl}}{x+11\bar{x}},\frac{\varphi_{back}(2)}{x},\frac{\varphi_{back}(0)}{x+\bar{x}}]$$

4.2.3 Flow level analysis

- Markov analysis of the flow level capacity:

To analyze the flow level capacity, we need to consider the traffic characteristics in addition to the end-user throughput. Considering FTP-like elastic calls, where a mobile stays in the cell until downloading a certain file, the download time will depend on the throughput $T(\vec{x})$, itself depending not only on the number of users x, but also on their distribution among the different radio conditions (x_i). The steady-state probabilities $P[\vec{x}]$ can thus be analyzed using Markov chains, by inverting the generating matrix describing the transitions between the different states. Note that, to insure the stability of the system, an admission control must be imposed by fixing a maximal number of users in each WiFi cell X_{max}.

Knowing the steady state probabilities, we can obtain the probability of having less than a target throughput T_{min}:

$$C=\sum_{\vec{x};T(\vec{x})<T_{\min}}\Pr[\vec{x}]$$

(equation g)

and the blocking rate:

$$B=\sum_{\vec{x};\sum_{i=1}^{J}x_i=X_{\max}}\Pr[\vec{x}]$$

(equation h)

The probability of having at least one active user in the target cell can also be calculated by:

$$r_0=1-\Pr[\vec{x}=0]$$

(equation i)

The average number of users in the target cell is given by:

$$\bar{x}_0=\sum_{\vec{x}}\sum_{i=1^J}x_i\Pr[\vec{x}]$$

(equation j)

- Fixed point capacity analysis:

The throughput analysis described above shows that there is a strong interaction between the different cells in the network. The first interaction level comes from the inter-cell interference between neighboring cells. The second interaction comes from the backhaul, as an access point routes other-cell users in WiFi mesh networks.

This interaction can be solved by a fixed point approach based on a partial decoupling assumption. This consists in supposing that the instantaneous numbers of users in the different cells are independent, and that the dependence is only through the distribution of the number of calls in the neighboring cells. This is a good assumption because of the large number of cells interacting in the system, making the impact of these cells averaged at each access point.

a/ Fixed point analysis of the inter-cell interference: we first solve the interaction due to WiFi inter-cell interference. We propose the following fixed point algorithm, knowing the backhaul throughput:

Algorithm 1:

i. Begin by supposing that the cell is isolated. In this case, the exclusion region of the cell is its own area and $\Pr[x_{exc} = 0] = 1$.
ii. Calculate the throughput at each state as in equation (d) knowing the distribution of x_{exc}. Deduce the steady-state distribution $\Pr[\vec{x}]$ using Markov analysis.
iii. Calculate the distribution of the number of users in the exclusion region $\Pr[x_{exc}]$ using the calculated values $\Pr[\vec{x}]$ as shown in §4.21.
iv. Repeat iterations 2-3 until the distributions converge.

b/ Fixed point resolution of the backhaul interaction in the WiFi mesh networks: in WiFi mesh networks, the throughput at backhaul depends on the load of other WiFi cells sharing the backhaul connection or interfering on it. The following algorithm is used to analyze the flow level capacity of the network:

Algorithm 2:

i. Begin by supposing that the access point is alone in the network. The activity parameter of all other cells is then $r = 0$ and the number of users in other cells is $\bar{x} = 0$.
ii. Apply Algorithm 1 to calculate the performance metrics knowing r and $\bar{x}$ and taking into account the inter-cell interference. Deduce the activity parameter r_0 and the average number of users $\bar{x}_0$ (equations i and j) in the different classes of access points defined in §4.2.2.
iii. Calculate the average parameters r and $\bar{x}$ over the cells of the network. Use these calculated parameters as inputs for Algorithm 1.
iv. Repeat iterations ii and iii until convergence of r and $\bar{x}$. Deduce the performance metrics in the different access points of the network (equations g and h).

4.2.4 Numerical evaluation of the capacity

The radio access we consider is based on the IEEE 802.11b standard; it uses the 2.4 GHz band and allows four data rates: 1, 2, 5 or 11 Mbps. These rates can be achieved at distances equal to 88, 74, 70 and 62 meters, respectively. The maximal cell range is thus equal to 88 meters. As of the access, we consider the 802.11a system, with the achievable throughput described in Table 10.

Table 10: IEEE 802.11a Physical throughput

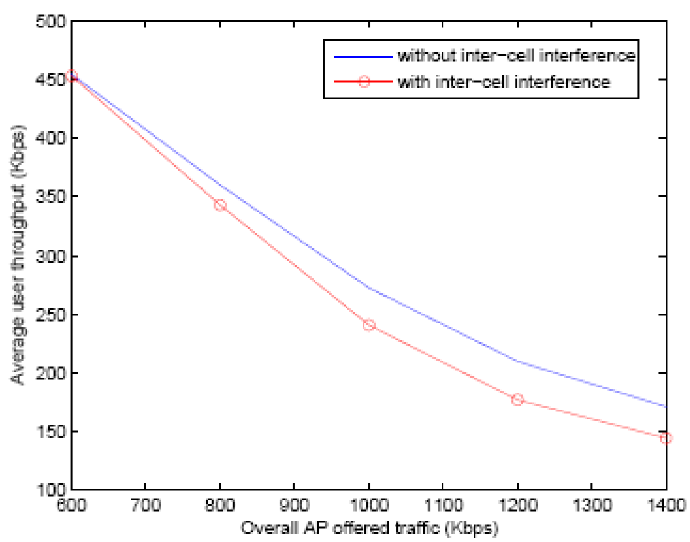
Throughput	Sensitivity	range (18 dBi gain)	range (12 dBi gain)
54 Mbps	-69 dBm	46 m	28 m
48 Mbps	-73 dBm	64 m	39 m
36 Mbps	-77 dBm	88 m	54 m
24 Mbps	-81 dBm	123 m	75 m
18 Mbps	-84 dBm	157 m	96 m
12 Mbps	-86 dBm	185 m	113 m
9 Mbps	-87 dBm	201 m	123 m
6 Mbps	-88 dBm	219 m	133 m

- Impact of inter-cell interference

We consider a reuse 3 WiFi deployment and study the impact of WiFi interference from the cells in the second ring (as the first ring access points use different radio channels). Considering that a signal received at less than -96 dBm is not sensed as a collision, the interference range is equal to 118 meters and 15% of cell edge users in a cell of the second ring are within this interference range ($\xi = 0.15$ in equation c).

Figure 23 shows the average throughput perceived by WiFi users versus the offered traffic by access point (in Kbps/AP), supposing that the backhaul throughput is not limiting. It can be seen that, when the interference from WiFi devices in the second ring is considered, the throughput decreases.

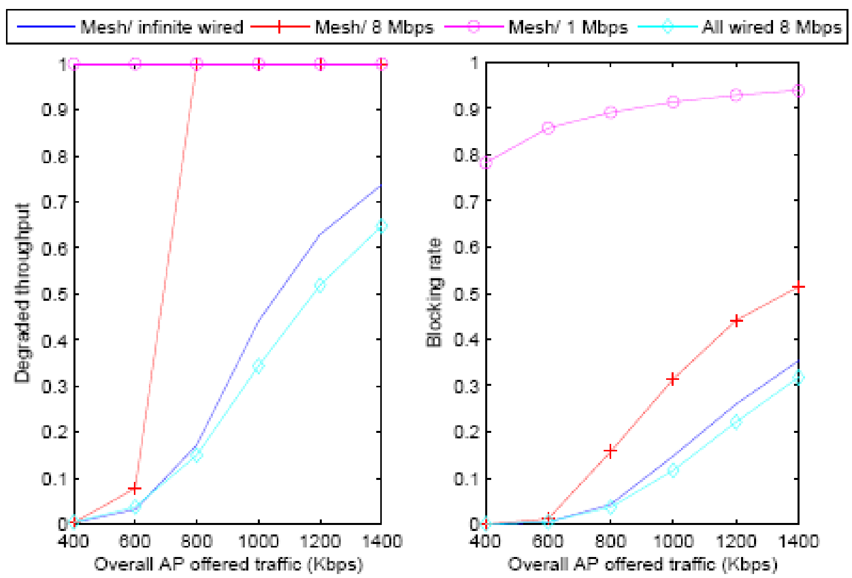
Figure 23: Average user-perceived throughput.



- Capacity of WiFi mesh networks

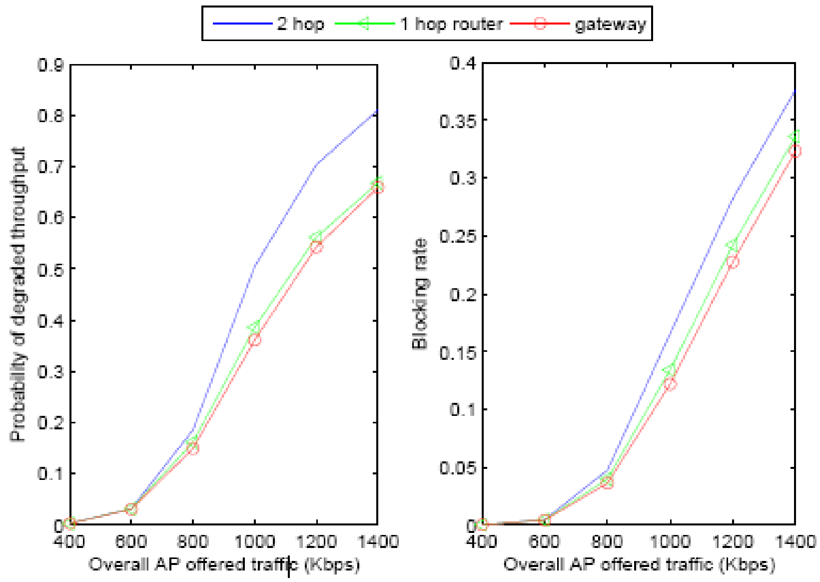
a/ WiFi versus wired backhaul: we consider the case of a 2 hop-max WiFi mesh network, whose gateways are connected to the Internet using a DSL like connection. Figure 24 plots the performance measures for different settings. The first one considers that the WiFi mesh gateways are not limited by the wired capacity (e.g. are linked to the Internet via fiber-optic connections); this setting is not necessarily realistic but allows to study the maximal capacity of WiFi mesh networks. The second and third scenarios correspond to a more realistic case where the gateways have a DSL connection of 8 and 1 Mbps respectively. The performance of an all-wired network where each AP has a 8 Mbps Internet connection is also plotted for comparison purposes. It can be seen that, in an ideal case, WiFi mesh networks perform quite well and are comparable to all-wired networks. However, when the gateways become limited by the wired capacity, the performance of the network degrades as a bottleneck is created by aggregating the traffic of several APs on a single connection.

Figure 24: Performance of WiFi mesh with different wired capacities.



b/ Impact of heterogeneous backhaul conditions: figure 25 shows the performance of the different classes of APs present in the network. In particular, we illustrate the performance of the gateways, the mesh routers (with 1 hop to destination) and the APs with two hops. It can be observed that the users whose APs have two hops before reaching the Internet have the worse performance, while the other users perform almost equally.

Figure 25: Impact of the number of hops.



- <u>Comparative note</u>

Based on the results presented above, we derive an Erlang-like capacity of the system to compare the different network implementations. Table 11 shows the maximal traffic that can be supported by an AP for a target blocking rate of 10% and when we impose that 90% of users have more than 128 Kbps. It can be seen that WiFi mesh networks offer a good QoS if the gateways are linked to the Internet by a good wired connection.

Table 11: Erlang-like capacity comparison

System	AP capacity (Kbps)
All-wired 8 Mbps	700
All-wired 1 Mbps	650
All-wired 512 Kbps	330
WiFi mesh 2 hop max / 100 Mbps	670
WiFi mesh 2 hop max / 8 Mbps	610
WiFi mesh 2 hop max / 1 Mbps	70
WiFi mesh 1 hop max / 8 Mbps	690
WiFi mesh 1 hop max / 1 Mbps	370

4.3 Case studies

In the following we will present three case studies and compare the capacity of HSDPA, WiMAX and EV DO. We differentiate between urban and rural areas and consider the following parameters:

Table 12: Traffic parameters.

	Urban	Rural
Population density (people/Km^2)	1000	100
Penetration (%)	Variable (0-20)	Variable (0-20)
Volume downloaded (Mbytes/day)	10	10
Traffic in busy hour (% of overall traffic)	10	10
Target DL throughput (Kbps per user`	256	64
Maximal number of users by cell	25	25

As for the QoS, we consider a target blocking of 10% and a target percentile for the throughput of 50% (half of the users will have more than the target throughput at the busy hour). The first QoS measure (blocking) is related to the capacity of the network, and the second (throughput percentile) is a user-perceived QoS measure.

<u>Note</u>: the limitation of the number of users in each cell is generally due to hardware limitations (number of channel elements or Iub capacity). In all cases, an admission control is necessary to avoid cell saturation. As there is generally a balance to find between blocking and user-perceived throughput, we consider jointly these two outputs. Note that the considered threshold (25 users) is large and is convenient to the best-effort kind of traffic we are dealing with. The result is that the throughput degradation comes, in most of the cases, before reaching the blocking target of 10%.

4.3.1 Constructing a coverage-limited network

When the aim of the operator is to minimize the number of deployed sites regardless from the capacity of the network, the dimensioning can be based on the above-described link budget analysis. Figure 26 to Figure 29 show the two QoS measures in this deployment for HSDPA and WiMAX. We do not show figures for CDMA 2000 1x EVDO as the capacity is too small.

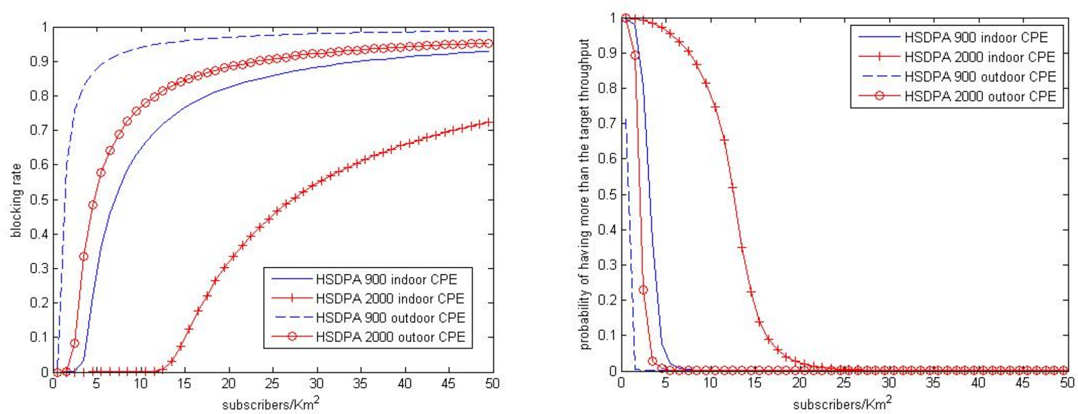


Figure 26: HSDPA QoS for coverage-limited cells in urban areas.

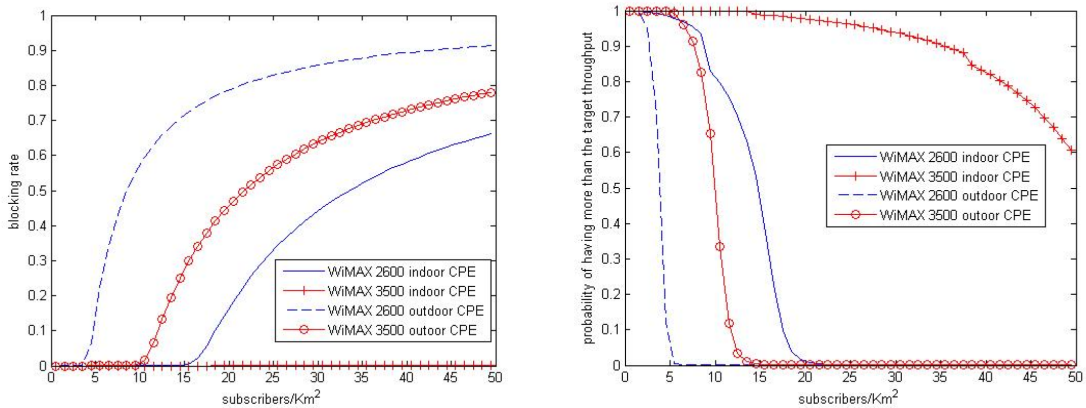


Figure 27: WiMAX QoS for coverage-limited cells in urban areas.

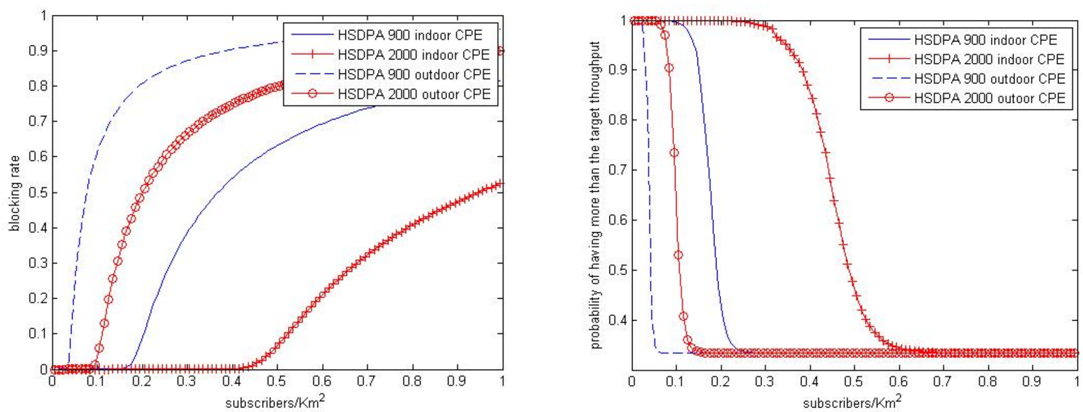


Figure 28: HSDPA QoS for coverage-limited cells in rural areas.

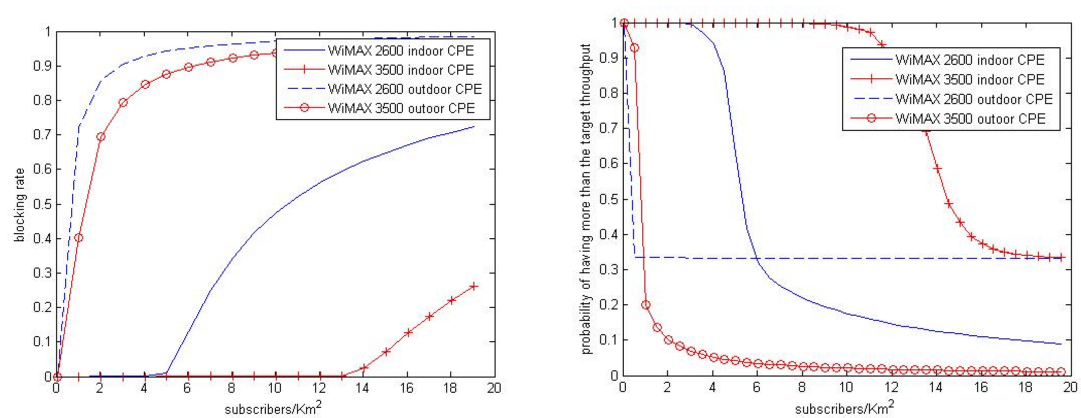


Figure 29: WiMAX QoS for coverage-limited cells in rural areas.

The following tables summarize the cell surface and the maximal capacity for the different situations for EVDO, HSDPA 900, HSDPA 2000, WiMAX 2600 and WiMAX 3500, for a target of 10% blocking and 50% throughput percentile.

Table 13: System capacity for coverage-limited cells

	Indoor CPE		Outdoor CPE	
EV DO 450	Urban	340 Km^2/cell	Urban	2640 Km^2/cell
		0.8 subscriber/ Km^2		0.1 subscriber/Km^2
	Rural	13678 Km^2/cell	Rural	99500 Km^2/cell
		0.024 subscriber/Km^2		0.004 subscriber/Km^2
HSDPA 900	Urban	58 Km^2/cell	Urban	400 Km^2/cell
		3.3 subscriber/ Km^2		0.6 subscriber/Km^2
	Rural	1440 Km^2/cell	Rural	9100 Km^2/cell
		0.2 subscriber/Km^2		0.04 subscriber/Km^2
HSDPA 2000	Urban	13.5 Km^2/cell	Urban	93 Km^2/cell
		12 subscriber/ Km^2		2.15 subscriber/Km^2
	Rural	534 Km^2/cell	Rural	3400 Km^2/cell
		0.5 subscriber/Km^2		0.11 subscriber/Km^2
WiMAX 2600	Urban	10 Km^2/cell	Urban	91 Km^2/cell
		15 subscriber/ Km^2		3.9 subscriber/Km^2
	Rural	32 Km^2/cell	Rural	706 Km^2/cell
		5.3 subscriber/Km^2		0.3 subscriber/Km^2
WiMAX 3500	Urban	4.5 Km^2/cell	Urban	38 Km^2/cell
		47.5 subscriber/ Km^2		10 subscriber/Km^2
	Rural	15 Km^2/cell	Rural	314 Km^2/cell
		15 subscriber/Km^2		0.65 subscriber/Km^2

It is obvious that the cell sizes obtained for EVDO, HSDPA, and even WiMAX 2600 are not realistic as the cells are huge and the supported capacity ridiculous. The conclusion is that the cells are coverage-limited only for WiMAX 3500 or when the density of subscribers is very low. A realistic dimensioning study, taking into account a target penetration for the proposed service, is proposed in the next section.

4.3.2 Reusing GSM sites for deploying the network

In this section, we consider the case where the telecommunications operator has an already deployed GSM network and find the capacity of the deployed network for each technology. We consider an urban area with a cell range of 2 Km and use the link budget tools to calculate the achieved throughput versus the distance to the base station for the different technologies, using outdoor or indoor CPE.

Figure 30 shows the throughput achieved for EVDO. In this case, we can see that the inter-cell interference is high at cell edge as the QoS is no more coverage-limited.

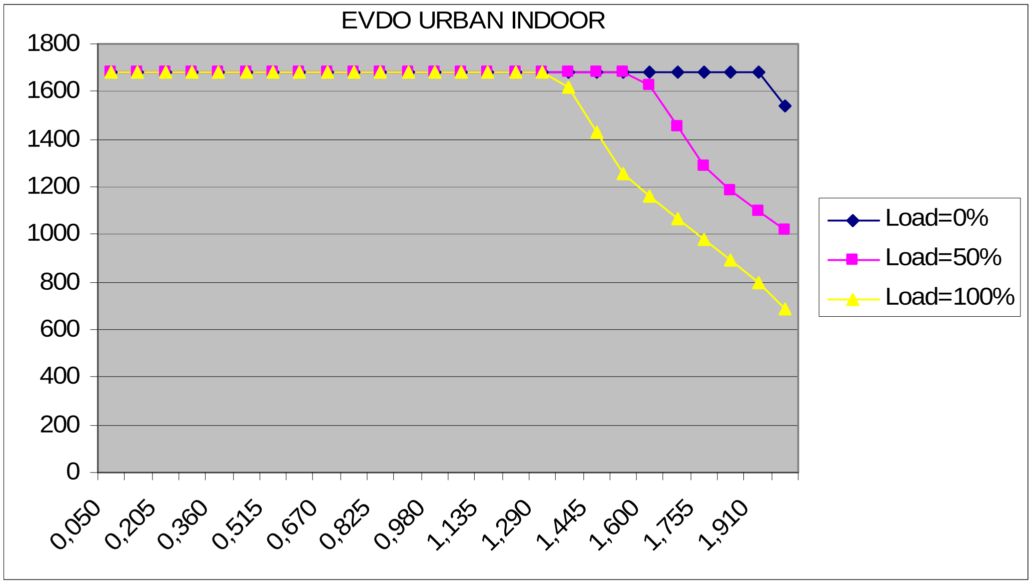


Figure 30: EVDO throughput versus distance when reusing GSM sites.

We plot in Figure ***31*** to Figure ***33*** the QoS (blocking and probability of achieving the target throughput) for the three systems. The first observation is that using outdoor CPE is useless for systems like EVDO or HSDPA 900 as there is no much impact on the QoS (the cell is not coverage-limited). Second, HSDPA 900 has the best capacity as it offers a good coverage and a high throughput. The problem of EVDO is its smaller bandwidth (1.25 MHz) that makes it throughput-limited compared to HSDPA 900, but still it has better capacity than HSDPA 2000 and WiMAX as it has a good cell-edge throughput.

Note: We did not draw the capacity for WiMAX 3500 as the cell is not fully covered in this case. The QoS target is thus never reached.

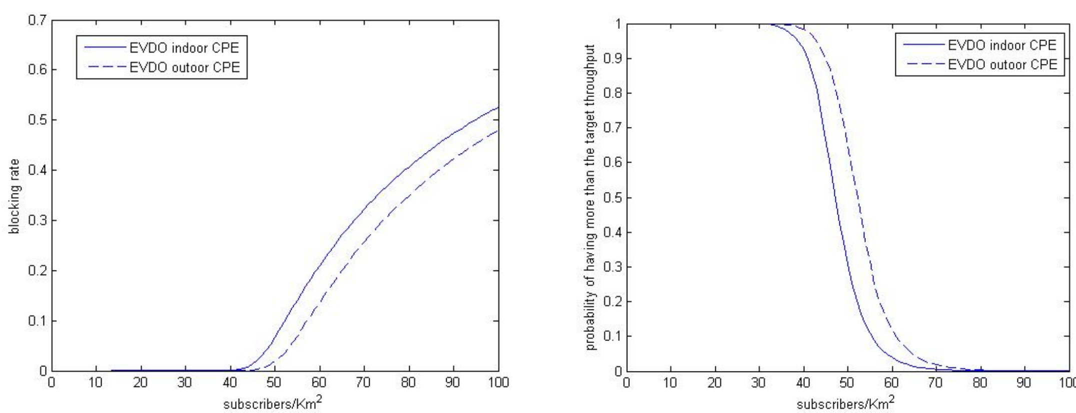


Figure 31: EVDO QoS when reusing GSM sites.

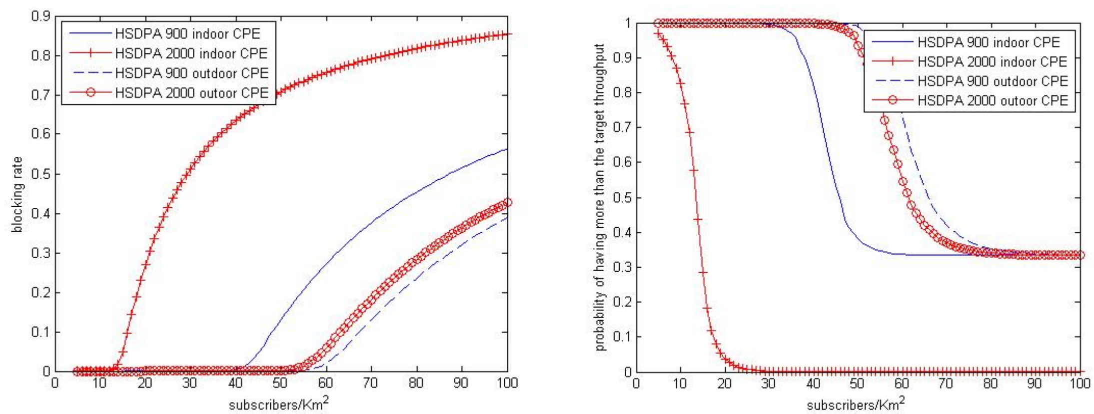


Figure 32: HSDPA QoS when reusing GSM sites.

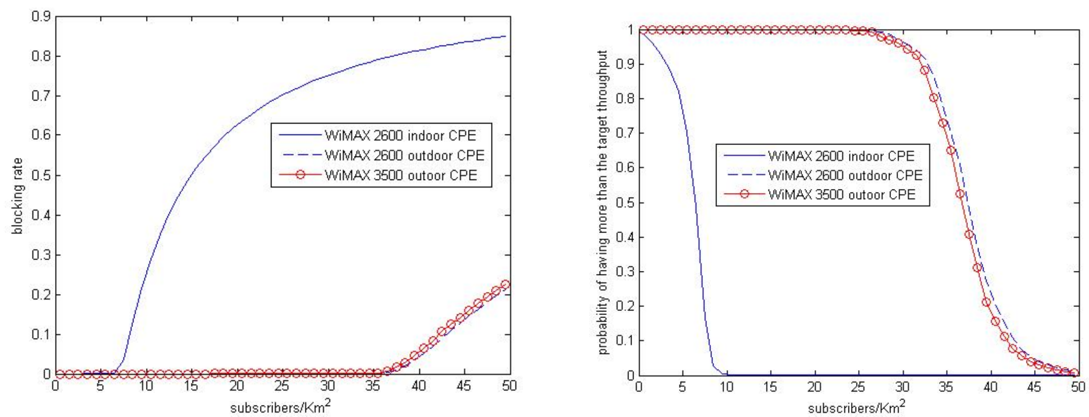


Figure 33: WiMAX QoS when reusing GSM sites.

The following table summarizes the maximal user capacity that can be served for each technology when reusing the GSM sites. The best capacity is when using HSDPA 900 with outdoor CPE. However, when using only indoor CPE, EVDO 450 is the best system, followed by HSDPA 900, far ahead from the other systems.

Table 14: Capacities of the different systems when reusing GSM sites.

System	CPE type	Capacity (subscriber/Km^2)
EVDO 450	indoor	47.5
	outdoor	52
HSDPA 900	indoor	46
	outdoor	66
HSDPA 2000	indoor	13.5
	outdoor	61.5
WiMAX 2600	indoor	7.5
	outdoor	37.5
WiMAX 3500	indoor	0
	outdoor	37

4.3.3 Dimensioning cells for a given traffic

In this section, we study the case where the telecommunications operator has a target penetration in some area and wants to deploy a network that gives a good QoS when this target penetration is attained, i.e. when the density of subscribers reaches a certain value. Another criterion to take is to minimize the number of cell sites in order to minimize costs. We take a target subscriber density of 50 subscriber/Km^2 (corresponding to a 5% penetration in a urban area with 1000 person/Km^2), and study the performance of the different systems for cells of radius 1, 2 and 3 kilometres, considering a deployment of indoor CPE only.

We can observe first that the QoS is rapidly degraded when cells are larger, as the traffic increases. Second, EVDO and HSDPA 900 achieve the best performances (EVDO is slightly better for blocking while HSDPA 900 is better for the per user throughput).

However, if the operator does not have the licences for deploying EVDO 450 or HSDPA 900 and has to deploy another system, this methodology can be used to find the optimal cell radius, i.e. the largest cell radius so that the QoS is acceptable. We recall that the methodology consists in using the link budget for calculating the throughput versus distance tables for the different cell radii, and then use the processor sharing analysis to assess the QoS.

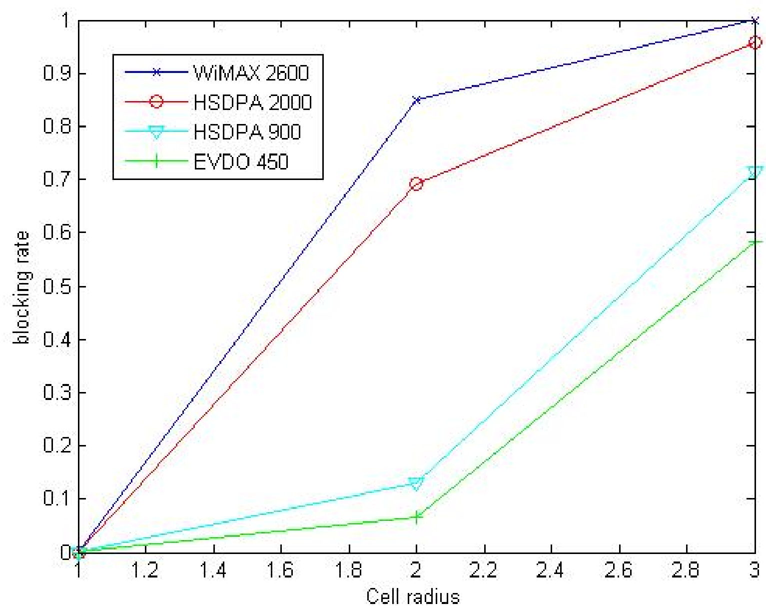


Figure 34: Blocking rates for a given traffic for different cell ranges.

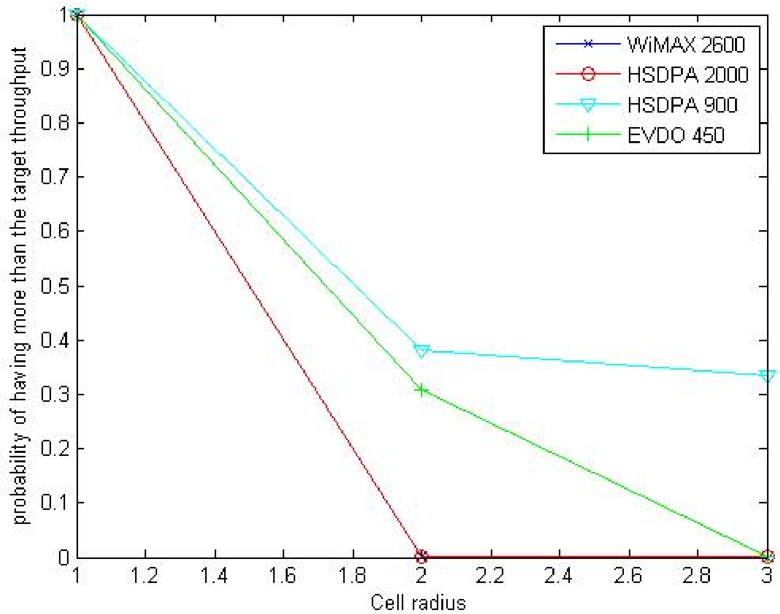


Figure 35: Probability of reaching the target throughput for different cell ranges.

5 VOICE SERVICE SUPPORT

This section aims at presenting QoS performances of each technology in or to determine the possibility to offer a VoIP service with appropriate QoS.

In order to offer a correct QoE (Quality of Experience) to a user the system must have:

- A QoS class allowing a minimum data rate guaranty. This minimum bit rate will depend on the VoIP codec used (e.g. 64kbps for G711).
- An acceptable round Trip delay.
- An acceptable jitter.

The QoE can also be measured by the Mean Opinion Score (MOS) value between 0 and 5 (5 is the best score) using an objective method (using a specific tool) or subjective method (users give a mark between 0 and 5).

The Following table aims at presenting VoIP border value.

Table 15: VoIP border value

Call Quality	Good	Average	Poor
Round trip delay	<150ms	150ms-400ms	>400ms
Jitter	<20ms	20ms-50ms	>50ms
Packet loss	<1%	<3%	>3%
MOS	> 4	Between 3 and 4	< 3

Note:
It is also possible to deploy a VoIP service without QoS on the access network. This could lead to QoE degradation when the network is loaded; however such a choice is a marketing choice.

5.1 HSPA/HSPA +

5.1.1 General overview of the UMTS QoS framework

In UMTS, several service levels have been defined by the 3GPP. The end-to-end service is provided between two terminal equipment (TE) applications. An end-to-end service is mainly supported by a UMTS Bearer Service which includes a Radio Access Bearer (RAB) service. The RAB service provides transport of signalling and user data between the mobile terminal and the core network edge node of the Iu interface. This transport is achieved with the QoS negotiated for the UMTS Bearer Service.

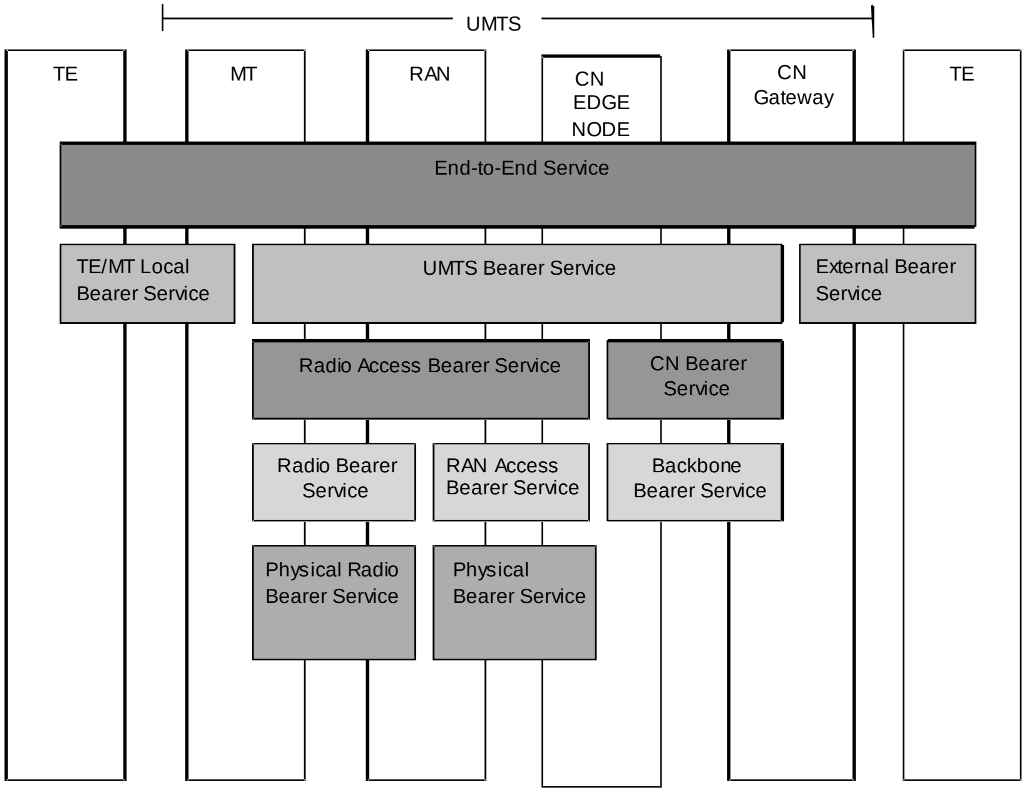


Figure 36: UMTS QoS architecture

A UMTS bearer service is characterised by a UMTS QoS class. When choosing the UMTS QoS classes, also referred to as traffic classes, the restrictions and limitations of the air interface have to be taken into account (bit rates, transmission delays…). The following table shows the four UMTS QoS classes.

Table 16: UMTS QoS class

Traffic class	**Conversational class** conversational RT	**Streaming class** streaming RT	**Interactive class** Interactive best effort	**Background** Background best effort
Fundamental characteristics	-Preserve time relation (variation) between information entities of the stream - Conversational pattern (stringent and low delay)	-Preserve time relation (variation) between information entities of the stream	-Request response pattern -Preserve payload content	-Destination is not expecting the data within a certain time -Preserve payload content
Example of the application	-voice over IP	-streaming video	-Web browsing	-background download of emails

For each QoS class, some QoS parameters are mandatory in order to guaranty a minimum data rate or delay. Table 17 presents the UMTS QoS parameter for each QoS class.

Table 17: UMTS typical QoS parameters

Traffic class	Conversational class	Streaming class	Interactive class	Background class
Maximum bitrate	X	X	X	X
Residual bit error ratio	X	X	X	X
Transfer delay	X	X		
Guaranteed bit rate	X	X		
Traffic handling priority			X	

For more details relative to the UMST QoS framework please refer to [7]

5.1.2 VoIP over HSPA

HSPA does not introduce new QoS mechanisms compared to UMTS and the same QoS framework is used. However, some improvement on the radio link should provide a better experience for real time application. The major improvements are:

- The scheduler is located in the BS in order to provide a better response to traffic requirement and channel condition
- The data rate is increased. This should allow increasing VoIP capacity.
- A new re transmission mechanism (Hybrid Automatic Repeat Request, HARQ) is implemented in the Node B. This should allow reducing application delay by avoiding some retransmission in the RNC (by the Radio Link Control, RLC).

Some tests were performed by Orange Labs in lab in 2007. In 2007 HSPA implementation, lots of features needed to provide an efficient VoIP service are not available. Indeed, current vendor implementation does not support real time QoS class (conversational and streaming) and RLC Unacknowledgement Mode (UM) is not implemented (this could increase dramatically mouth to ear delay in case of bad radio condition)

The main results of this study were:

- VoIP exhibits a good quality (MOS between 3.5 and 4), even in loaded condition, in good radio condition
- At the cell edge, the mouth to ear delay increase significantly. Indeed, UM RLC mode is not implemented and many retransmissions take place in the RNC.

However, all features needed to support an efficient commercial VoIP service (Conversational QoS class, Header compression …) will be implemented by vendor by Q3 2009.

For more detail relative to the perceived quality over HSPA, see [14].

5.1.3 VoIP over HSPA+

HSPA+ is natively designed to support real time application such as VoIP. Indeed, in HSPA+, the RNC Packet Switch functionalities are implemented in the Node B. In other words, all retransmission mechanisms (at the MAC and at the RLC level) are implemented in the Node B. This should highly reduce packet retransmission time and avoid having a too high mouth to ear delay even in bad radio condition (as described in HSPA section).

5.2 EDGE/EDGE evolved

5.2.1 VoIP over Edge

EDGE allows data rates on shared resources permitting to provide a throughput of up to 200 kbps per user. But, EDGE, in its current deployed version, is designed for the support of Background and Interactive services needing a significant throughput but not requiring stringent constraints in term of delay as real time IP based services. For example, as HSDPA, currently it does not ensure a guaranteed bit rate.

However, a function called Packet Flow Control (PFC) is implemented by some vendors. This function provides QoS classification of flows in the BSS according to the traffic type in order to provide QoS on the air link. In other words, this function could guaranty data rate and delay on the air link if conversational QoS class is supported by the access network.

For more detail on the PFC function, see [15].

5.2.2 VoIP over Evolved Edge

No information available for now.

5.3 CDMA 2000

1xEV-DO release 0 does not provide QoS mechanisms by itself. However, by software upgrading, inter user differentiation can be performed (but not inter application)

To fill in the QoS gap of 1xEV-DO, Rev A has adopted a flow-oriented QoS architecture that allows the network to provide differentiated treatment to separate application flows, even when the applications are associated with the same device. To deliver such differentiated treatment, EV-DO Rev A utilizes higher layer protocols between the network and the handset to set up and configure these flows based on the needs of the applications. By doing so, Rev A can handle separate flow types with differentiated levels of service, across the network. This allows Rev A to assure the delivery of critical delay-sensitive traffic flows like VoIP even in the presence of loaded best effort traffic.

No tests were performed on CDMA 2000 network for VoIP service. However, according to vendors, there is no problem to support such a service when using Rev A (in term of delay and data rate guaranty). These values can be trusted since measurement performed during trial [16] for BE service shows a delay of about 125 ms.

5.4 WiMAX

5.4.1 General WiMAX QoS concept

The central concept of the WiMAX QoS model is the notion of Service Flow. A service flow is a MAC transport service that provides unidirectional transport of packets either to uplink packets transmitted by the MS or to downlink packets transmitted by the BS. MS and BS provide QoS according to the QoS Parameter Set (such as latency, jitter, and throughput assurances) defined for the considered service flow. Five QoS classes are available in WiMAX; the following table describes these QoS classes:

Table 18: WiMAX typical QoS parameter

QoS class	Typical application	Typical QoS parameters
UGS	VoIP	- Maximum Sustained Traffic

Unsolicited Grant Servic		Rate - Maximum Latency - Tolerated Jitter
rtPS Real-Time Polling Service	Video streaming Audio streaming	- Minimum Reserved Traffic Rat - Maximum Sustained Traffic Rate - Maximum Latency
ertPS extended real-time Pollin Service	VoIP with silence suppression Gaming	- Minimum Reserved Traffic Rat - Maximum Sustained Traffic Rate - Maximum Latency - Tolerated Jitter
nrtPS non-real time Polling Service	FTP Data base	- Minimum Reserved Traffic Rat - Maximum Sustained Traffic Rate
BE Best Effort	Peer to Peer Web browsing	- Maximum Sustained Traffic Rate

For VoIP service, UGS or ertPS QoS can be used. Indeed, these QoS classes are designed for VoIP services (data rate, Delay and Jitter guaranty).

5.4.2 VoIP over WiMAX

As described in previous section, WiMAX is natively designed to support real time application such as VoIP. Regarding delay and Jitter, Field test performed by Orange Labs gives the following results:

- Delay for VoIP QoS class: ~ 84 ms (one way delay)
- Jitter for VoIP QoS class: ~17ms (using UGS QoS class)

For more detail relative to field test, please refer to [8]

Also, MOS measurements were performed on an e-ready system (software upgradable to 16e, same QoS mechanism than 16e) using Orange operational network mirror platform. The MOS obtained were superior to 4.

For more detail relative to these End to End VoIP tests, see [17].

5.5 WiFi mesh

No information available for now.

5.6 VoIP service support comparison

The following table aims at presenting the summary of VoIP service support for each technology. It is to be noted that mussing information will be include in next release of the document.

Table 19: VoIP service support comparison

	Data rate guaranty		Latency		Jitter	
HSPA	Not implemented i current release	😐 Q3 2009 ☺	< 400ms in good radio condition > 400ms in bad radio	😐 Q3 2009 ☺	No Conversationa QoS class	😐 Q3 2009 ☺

			condition			
HSPA+	Should be implemented	☺	Should be good	☺	Should be good	☺
EDGE	Mechanism exists but not tested.	😐	Unacknowledgment mode not implemented	☹	No test performed for conversationa QoS class	😐
EDGE Evolved	Should be better than Edge	No data	Should be better than Edge	No data	Should be better than Edge	No data
CDMA 2000	Rev A is designed for VoIP service	☺	~ 125 ms	☺	No value	?
WiMAX	Yes	☺	~ 84 ms	☺	~17ms	☺
WiFI	No informatior available for now.		No information available for now.		No information available for now.	

For HSPA+, WiMAX and CDMA 2000 Rev A, QoS mechanisms and radio performances will allow to deploy a VoIP service offering a high quality call. However for HSPA+, since no product will be available before 2009, VoIP quality should be assessed when available.

For HSPA, 2008 product does not implement all features needed to deploy a VoIP service with QoS. For 2009-2010 timeframe all function needed will be implemented (in Q3 2009) by vendors and so VoIP service should be available for HSPA.

For Edge, it will be not possible to offer a VoIP service since mouth to ear delay is too high in bad radio condition.

No information are available at present for WiFi mesh and Edge Evolved.

6 SYSTEM ARCHITECTURE OVERVIEW

This sections aims at presenting a high level overview of the network architecture for each technology. A brief description of each network element and the list of the minimum equipment needed to deploy a broadband network are given.

6.1 EDGE/EDGE evolved

6.1.1 EDGE architecture

EDGE/EGPRS is a superset to GPRS and can function on any network with GPRS deployed on it. As EDGE is a GPRS enhancement there is very little modification to be completed within a GPRS enabled core network. In the access network, transceiver (TRX) must be replace or update (possibility to add several TRX per Base Station).

Figure 37 shows the EDGE/GPRS architecture.

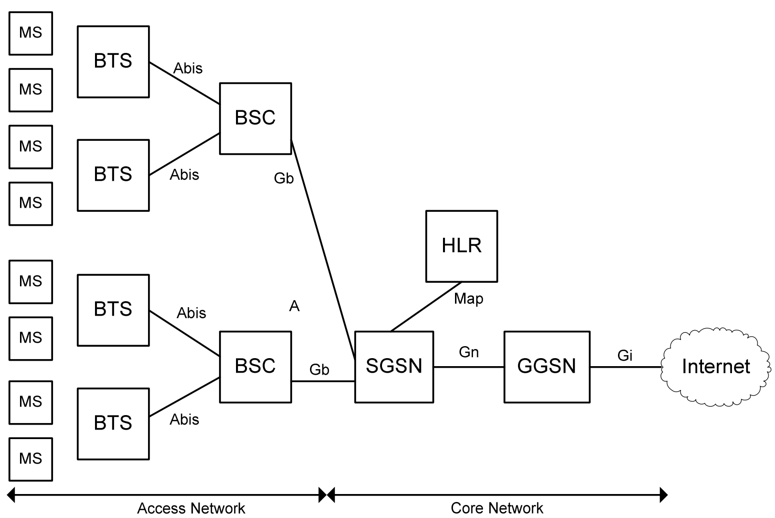


Figure 37: EDGE architecture

The access network is composed of:

- The Base Transceivers Station (**BTS**): The BTS contains the equipment for transmitting and receiving of radio signals (transceivers), antennas, and equipment for encrypting and decrypting communications with the Base Station Controller (BSC)
- The Base Station Controller (**BSC**): The BSC acts as a concentrator for BTS traffic. It also handles allocation of radio channels, receives measurements from the mobile phones and controls handovers from BTS to BTS. The BSC is connected to the SGSN in the Packet Switch (PS) domain.

The PS core network is composed of:

- One or more Gateway GPRS Support Node (**GGSN**): The GGSN serves as the interface towards external Packet Data Networks (PDNs) or other Public Land Mobile Networks (PLMNs).
- One or more Serving GPRS Support Node (**SGSN**): The SGSN represents the GPRS switching center in analogy to the Mobile-services Switching Center (MSC) in the Circuit Switch (CS) domain. The SGSN is responsible for the routing inside the packet

radio network and for mobility and resource management. Furthermore, it provides authentication and encryption for the GPRS subscribers.

- Home Location Register (**HLR**): The HLR is a central database that contains details of each subscriber that is authorized to use the GSM core network. There is one logical HLR per PLMN (Public Land Mobile Network), although there may be multiple physical platforms.

The transport layer on the access network part can be ATM based. Evolution toward IP based transport is planned.

Mandatory equipment to deploy an EDGE network: MS, BTS, BSC, SGSN, GGSN and HLR

6.1.2 EDGE Evolved architecture

No information available for now.

6.2 HSPA/HSPA +

6.2.1 HSPA architecture

HSPA is an evolution of the Packet switch domain of the UMTS (of the UTRAN) and improve radio performances of the radio link (UL and DL).

Figure 38 shows the HSPA Packet Switch domain architecture.

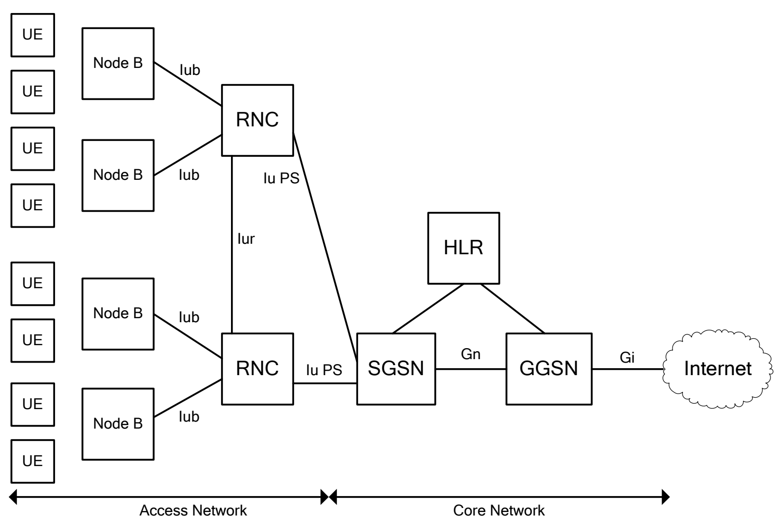


Figure 38: HSPA architecture

The access network is composed of:

- Radio Network Controller (**RNC**): The RNC is responsible of the control of the Node Bs in the access network (UTRAN). The RNC carries out radio resource management, some of the mobility management functions and is the point where encryption is done before user data is sent to and from the mobile. The RNC connects to the SGSN in the Packet Switched Core Network.
- **Node B**: Node B contains radio frequency transmitter(s) and the receiver(s) used to communicate directly with the mobiles. Additionally in HSPA, some function (like packet retransmission) implemented in the RNC for UMTS are now implemented in the Node B in order to improve user experience and data rates.

- User Equipment (**UE**): The UE is the HSPA device.

The PS core network is the same as the GPRS core network (with enhanced capacity).

The transport layer on the access network part can be ATM based or IP based.

Mandatory equipment to deploy a HSPA network: UE, Node B, RNC, SGSN, GGSN and HLR

6.2.2 HSPA+

The HSPA+ architecture is an evolution of the HSPA architecture. This architecture is usually called 'flat' architecture since all the RNC functionalities (relative to the PS domain) are moved to the HSPA+ Node B (by software upgrade of the PS part) which is now directly connected to the SGSN.

Figure 39 shows the HSPA+ architecture.

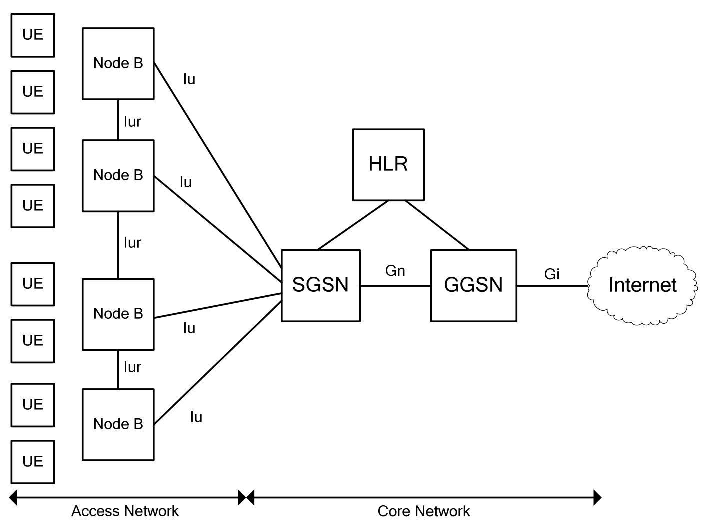


Figure 39: HSPA+ architecture

The HLR, SGSN and GGSN have the same function as in the HSPA world. The main differences between HSPA and HSPA+ PS core domain is that the capacity of HSPA+ equipment has to be higher (or more equipments have to be deployed).

The transport layer on the access network is IP based.

Mandatory equipment to deploy a HSPA+ network: UE, Node B, SGSN, GGSN and HLR

For more detail relative to the HSPA+ architecture refers to [11].

6.3 CDMA 2000

As for UMTS network, there are also CS domain and PS domain.

Figure 40 shows a high level overview of the PS CDMA network architecture.

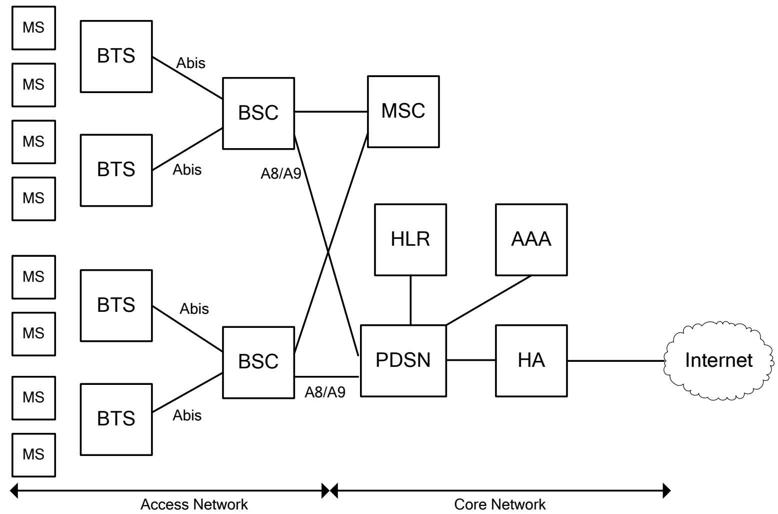


Figure 40: CDMA2000 architecture overview

The access network is composed of:

- A Base Station Controler (**BSC**): The BSC is responsible for controlling and managing the BTSs, setting up and releasing call connections, implementing handoffs to ensure reliable radio connections for upper-layer services, implementing power control, and managing radio resources. The BSC also embeds the Packet Control Function (PFC) which controls the packet session over air interface.
- Base Transceiver Station (**BTS**): The BTS supports power control and rate control, handoff, radio and channel configuration. It has the same functionality as in 3GPP network.
- Mobile Station (MS): The MS is the CDMA device

The transport layer on the access network part can be ATM based or IP based.

The Core network is composed of:

- A Packet Data Service Node (**PDSN**): the PDSN has the same functionality as GGSN in UMTS network.
- A Mobile switching Center (**MSC**): The MSC manages user authentication and user mobility for both the CS and PS domain.
- A Home location register (**HLR**): The HLR has the same functionality as in UMTS network.
- A Home Agent (**HA**): The HA is a router on a mobile node's home network which tunnels packets for delivery to the mobile node when it is away from home, and maintains current location information for the mobile node.
- An Authentication, authorization and Accounting (**AAA**): The AAA server is responsible of the authentication and for the billing for a user.

Mandatory equipment to deploy a CDMA 2000 network: MS, BTS, BSC, PDSN, MSC, HLR, AAA and HA

For more detail relative to the CDMA network architecture, see [16].

6.4 WiMAX

The WiMAX architecture is one of the first all IP architectures implemented in Wireless networks. The network is composed of an access network (Access Service Network, ASN) and a core network (Connectivity Service Network). The ASN provides the WiMAX access infrastructure and the CSN provides IP connectivity to user.

Figure 41 shows a high level overview of the network architecture.

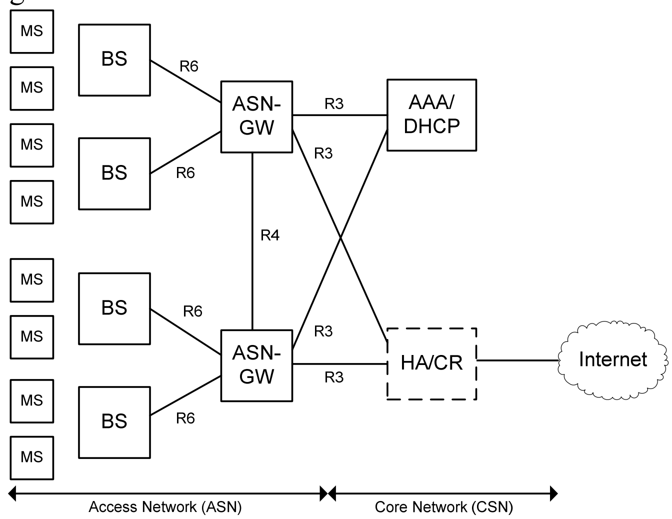


Figure 41: WiMAX architecture

The ASN is composed of:

- **ASN-GW(s)**: This functional entity acts as a Base Station (BS) controller and is the interface between the access and core network.
- **Base Station** (BS): The WiMAX Base Station is a logical entity that embodies a full instance of the WiMAX MAC and PHY layers. It incorporates scheduler functions for uplink and downlink resources,
- **Mobile station** (MS): Generalized stationary equipment set providing connectivity between subscriber equipment and a base station (BS).

Note: ASN-GW and BS are logical entities in the specification. Regarding physical aspects, ASN-GW and BS can be implemented in a single or in separate physical boxes (depending on the ASN vendor).

The CSN is composed of:

- A **AAA server**: The Authentication, authorization and Accounting (AAA) server is responsible of the authentication and for the billing for a user
- A **DHCP server**: The DHCP server is responsible for allocating IP address to the WiMAX device. The DHCP server can be implemented in the AAA server
- A **Home Agent** (HA): The HA is a router on a mobile node's home network which tunnels packets for delivery to the mobile node when it is away from home, and maintains current location information for the mobile node. The HA can be removed from the CSN when deploying a stationary network (i.e. without mobility needs) and is replace by a **Core Router** (CR, a router without any specific function)

Mandatory equipment to deploy a WiMAX network: MS, BS, ASN-GW, AAA server, DHCP server and Core router.

6.5 WiFi mesh

The notion of wireless mesh networks is very large; a basic definition could be a multi-hop system in which mobile or fixed nodes collaborate in transmitting packets through the network.

Nodes send and receive users' data but also relay the traffic of neighbours toward destination that could be for example the gateway or any other node of the network. Each node regularly updates all its neighbouring radio link states, and then allows the mesh network to offer multiple redundant communications paths throughout the network.

Figure 42 shows a high level overview of the WiFi mesh architecture.

Note: The standardization of the WiFi mesh is not finished and different kinds of architectures are proposed by WiFi mesh vendors.

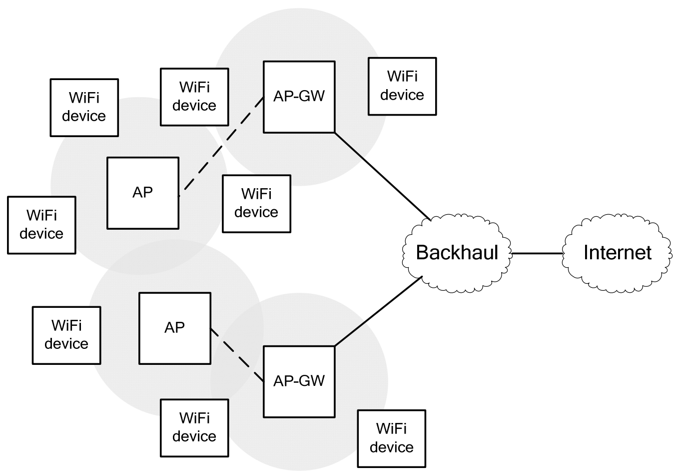


Figure 42: WiFi mesh architecture overview

The Access network is composed of:

- WiFi device: The client terminal which embeds a WiFi client
- Access point (**AP**): Each AP has 2 main functions. The access function in order to provide WiFi connectivity to user and a backhaul function in order to forward user's data, through the relaying process using dynamic multi-hop technologies.
- Access Point GateWay (**AP-GW**, depend on vendor implementation): Specific AP which provides connections between WiFi mesh network and the transport network. This node can also perform user authentication.

For more detail relative to the WiFi mesh architecture, please refer to [12].

Mandatory equipment to deploy a WiFi mesh network: WiFi device, mesh AP and AP-GW

Note: WiFi mesh standardisation is in progress. When completed, the architecture will be defined and proprietary solutions will disappear.

6.6 Architecture comparison

In the previous sections, a high level overview of each network architecture was presented.

For 3GPP/3GPP2 system (EDGE, HSPA, CDMA 2000), Packet Switch architecture is very similar with an access network composed of Base Stations and Base Station Controllers and a core network composed of a GGSN, SGSN and HLR (MSC and PDSN for CDMA 2000). The migration from GPRS to Edge or from EDGE to HSPA (or from CDMA 2000 EVDO Rev 0 to

Rev A) does not need an hardware upgrade of the PS core network if PS core network capacity still sufficient after migration (since data rate in the access network will increase).

WiMAX provides a very simple all IP architecture with few elements in the core network (only a AAA server with embedded DHCP function) reducing needed OPEX and CAPEX. It has to be noted that architecture evolution is toward reducing the number of nodes in the network (e.g. RNC in Node B for HSPA+)

For WiFi mesh, the architecture is also very simple but standardization process is not finished and many proprietary solutions are implemented.

7 CONCLUSION

In this deliverable, we presented a comparative study of the coverage, capacity and architecture of the candidate systems for offering a wireless internet service in emerging countries. We focused on CDMA 2000 1x EV DO, HSDPA, WiMAX and WiFi. The main conclusions are as follows:

- The coverage is extremely related to the frequency, making cells in 1x EVDO very large.
- Using an outdoor CPE is useful only for far isolated users or when the frequency is very high (e.g. WiMAX 3500).
- When reusing existing sites, 1x EV DO and HSDPA 900 support large capacities.
- For a target traffic intensity, an optimal cell range can be found for each technology that minimizes the costs while guaranteeing the target QoS.
- WiFi mesh networks offer a good QoS when the gateways are linked to the Internet by a good wired connection.
- 3GPP/3GPP2 systems (EDGE, HSPA, CDMA 2000) have the same network PS architecture. The core network can thus be reused when upgrading between these systems.
- WiMAX has the simplest all IP architecture, while the WiFi Mesh all IP architecture is still in standardization.
- All systems, except EDGE, support (or will support) voice over IP with a good QoS.

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