WiMAX
A new Star at the Horizon ?

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WiMAX recently has gained a lot of attention as a new revolutionary wireless technology. Following the claims of many marketing people, it can be seen as the key to a universal broadband and even mobile wireless access outperforming existing solutions such as Wireless LAN (also known as WiFi) and UMTS (3G). This white paper is intended to investigate the technical and regulatory background and tries to describe the performance that can be expected and the associated application scenarios under realistic assumptions.

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➢ Some historic background, lessons learned

Broadband wireless access with the capability to provide wide area coverage (Wireless MAN) serving as an alternative to DSL is available since mid of the 90's . Nevertheless, looking at analyses investigating the market penetration, DSL is the clear winner by far. Despite the obvious and attractive features of broadband fixed wireless access, real world deployments were characterised by a series of boundary conditions limiting or even inhibiting the successful application. As always, there are several reasons for that, but the main issues were related to regulatory and commercial topics and less related to technical or performance problems. Most of the better solutions offered since mid of the nineties were technically quite powerful but widely proprietary and consequently by far too expensive. Limited to the more professional part of the market, none of the suppliers was able to reach a quantity level facilitating the necessary economies of scale for a true mass market. On top of that, operators and suppliers had to work on a complex landscape of regulatory constraints with a multitude of regional boundary conditions and specifics inhibiting a fast and effective rollout. Despite all these problems, there are some examples of successful deployments verifying the competitive edge of the technology as such.

➢ Global Standards are the Key to Mass Markets

Other innovative wireless access technologies such as Wireless LAN and UMTS clearly show the way to success: creating global standards for interoperability at the air interface enables sharing of the development efforts for suppliers and guarantees a minimum of associated risks. Leading chip manufacturers consequently are willing to invest in large scale integrated circuits enabling even complex technical solutions to be extremely powerful and low cost at the same time. On this basis, international standardisation bodies (IEEE and ETSI) have started activities for wireless MAN standardisation in the end of the nineties (for an overview see Figure 1)

On top of the standardisation activities which are partly redundant (i.e. IEEE and ETSI are conducting activities in the same area but not fully harmonised), interest groups have been created to push the standardisation activities for a faster time to market, addressing promotion, marketing, profiling, regulatory, testing and certification areas. The most important industry fora in that respect are the WiFi (WiFi = Wireless Fidelity) Alliance and the WiMAX Forum (WiMAX = Worldwide Interoperability for Microwave Access). In the WiFi area, IEEE 802.11 in various versions has been established as the leading standard, whereas ETSI HiperLAN/2 has not gained wide attention.

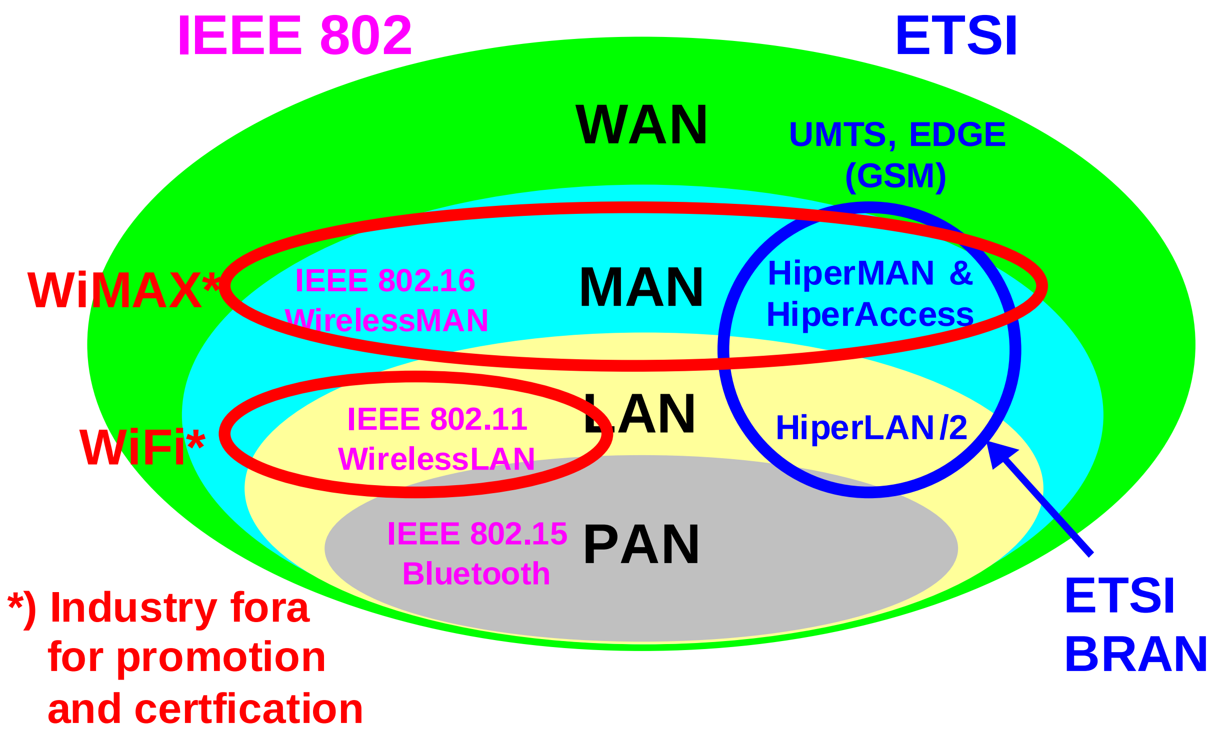


Fig. 1: **Overview of general standardisation activities in IEEE and ETSI**

Looking at the wireless MAN area, Table 1 gives a more in depth view of the different activities and the status of the standardisation. Current activities in the WiMAX Forum and associated product developments at various manufacturers and subsequent rollouts focus on IEEE 802.16-2004 WirelessMAN systems (fixed broadband wireless) and in the near future on IEEE 802.16e (extension to mobile broadband wireless), in the ETSI area, products have been developed and are being rolled out focusing on the ETSI BRAN HiperAccess standard (e.g. Marconi AXR).

Standard	IEEE		ETSI	
	Name	Status	Name	Status
High frequencies (LOS) Fixed access	IEEE 802.16 (replaced by 802.16-2004)	published 2001	**BRAN HiperAccess**	published 2002
Low frequencies (NLOS) Fixed access	IEEE 802.16a (replaced by 802.16-2004)	published 2003	BRAN HiperMAN	published 2004
Low frequencies (NLOS) Fixed access WiMAX system profiles	**IEEE 802.16-2004**	published 2004	BRAN HiperMAN (Harmonised)	ongoing
Low frequencies (NLOS) Mobile access including roaming between service areas	IEEE 802.16e	expected 2005	n.a.	n.a.
Low frequencies (NLOS) with full mobility incl. handover and roaming	IEEE 802.20 (status unclear), IEEE 802.22 (TV bands) IEEE 802.21 (roaming)	expected 2007/8	n.a.	n.a.

Table 1: Time line of standardisation activities in IEEE and ETSI in broadband wireless access

Other standardisation activities are either not that strongly promoted (like ETSI BRAN HiperLAN) or are still too premature to be deployed in short term (like IEEE 802.16e, IEEE 802.20 and IEEE 802.22). Furthermore, activities are under way to further harmonise the work of IEEE and ETSI in order to migrate to a more unified picture.

This has recently in particular been achieved for the harmonisation of IEEE 802.16-2004 and ETSI BRAN HiperMAN. Both parties and the WiMAX Forum are closely co-operating in joining forces and leveraging skills and experiences from all sides.

- **What performances can be expected ?**

Global standardisation activities relate to different areas of wireless access: micro- and picocellular (short range) technologies such as DECT (Digital European Cordless Telephone), Bluetooth and WLAN, by definition not suited for wider area coverage and mobile technologies with much better area coverage capabilities such as GSM, UMTS or similar standards in other parts of the world. While these technologies are able to cover larger areas, they are bandwidth limited due to the requirements for mobility, bandwidth availability and some characteristics of the air interface.

Consequently, there was/is still a need for more powerful air interface standards providing improved area coverage (link range) and higher throughput and system capacity at the same time. In terms of area coverage, current mobile systems define the state-of-the-art. The user bandwidth is driven by DSL performance and QoS (Quality of Service), where at least several Mbit/s (committed data rate) are provided to the individual user.

For a simplified classification of the major air interface parameters for lower frequencies we assume the following:

Area coverage:	Low	very short range communication with a range of several meters to several 10 meters
	Medium	short range communication with a range of up to a few 100 meters
	High	link ranges above 1 km up to several km (and more)
User data rate:	Low	Data rates < 100 kbit/s
	Medium	Data rates < 1 Mbit/s
	High	Data rates in excess of 1 Mbit/s, up to 10 Mbit/s and more

All parameters refer to “normal” operational conditions. For wireless systems this means:

- a cellular environment (automatically including a certain level of self-interference),
- a reasonable level of traffic load and system capacity (e.g. a certain number of active users with committed traffic per radio cell) and
- a reasonable to low effort for terminal (CPE, Customer Premises Equipment) installation

Based on the classification shown in Table 2, WiMAX is the only air interface technology that is in principle able to compete with DSL in terms of coverage and user bandwidth.

Standard	User Data Rate	Area Coverage
DECT	Low	Low to Medium
Bluetooth	High	Very Low
GSM (2G, 2.5G)	Low	High
UMTS (3G)	Medium	High
UMTS (HSDPA)	High	Medium
WLAN (WiFi)	High	Low
DSL	High	High
WiMAX	High	High

Table 2: Comparison of different standardised air interface technologies for NLOS conditions and their expected performance in comparison to DSL

Looking at the residential market, there is another specific aspect that has to be taken into account. The air interface must be able to work in a NLOS (Non-Line Of Sight) mode, i.e. transmitter and receiver are not always “visible” to each other. A pure LOS (Line of Sight) operation would require a more professional CPE installation with an outdoor antenna which is not always possible or desired. NLOS scenarios can vary substantially, from a slightly obstructed LOS path (OLOS, e.g. given by trees growing into the wireless link or simply by foliage attenuation) in the best case, to a fully obstructed link with high additional attenuation (e.g. for scenarios where building and wall penetration is required) in the worst case. Such limiting constraints can dramatically reduce the performance shown above as it is well known from existing mobile systems. In order to understand these issues, a more in-depth technical evaluation is necessary.

In any case, the theoretically possible performance parameters have to be carefully mapped to real world scenarios. This typically reduces the expected performance and needs to be taken into account when evaluating different technologies. Over-hyped expectations that are only valid in best-case scenarios or under unrealistic boundary conditions normally are counterproductive.

- **Some more technical aspects**

Advantages and disadvantages of different air interface technologies are better understood looking at some basic physical principles and traffic theory aspects that have to be taken into account, mapping these on the specific boundary conditions of the individual situation. In that context, the most important system aspects can be summarised as follows:

- Obtaining reasonable coverage under NLOS constraints, related to the effective link budget
- Managing a very dynamic, non-predictable and time-variant transmission channel
- Providing high transmission capacities in a coverage area taking into account that frequency resources are very limited
- Providing high user data rates under these circumstances even with a certain traffic load
- Quality of service (low error rates, low latency, committed data rates etc.) under all these circumstances

Besides these more general (and partly conflicting) principles, a lot of regional specifics have to be considered. These are mostly determined by individual regulatory rules that can degrade the theoretically maximum performance. As an example, many regulatory bodies have installed rules to limit the power flux density of radio transmitters. Obviously, this may reduce the link range and deteriorate the coverage.

Looking first at coverage and propagation aspects, we can conclude that this is primarily determined by the frequency of the radio carrier. For Figures 2 to 4 we assume a typical urban outdoor propagation scenario where the central station is located below the average rooftop level and a direct LOS path is only possible in small parts of the coverage area. Due to the physics of diffraction and reflection of the electromagnetic waves, the power density in the coverage area degrades rapidly with increasing frequency. As a result of that, at 900 MHz still a reasonable level of coverage is maintained where at 5 GHz or even at 10 GHz only micro- or pico-cellular coverage can be achieved. Therefore, frequencies above 3 GHz to 5 GHz tend to be not perfectly suited for NLOS coverage in larger areas. These frequency bands are more suited for LOS or slightly obstructed LOS scenarios. This becomes even more stringent if in-building penetration is required. Transmission attenuation through different types of wall material are also strongly frequency dependent and generally increase with increasing frequency. As a consequence, true NLOS with acceptable coverage is limited to low frequencies where the bandwidth resources are rare and have to be shared with many other systems and services, in particular cellular mobile. This bandwidth shortage has in some cases led to tremendous costs for frequency licenses (e.g. UMTS).

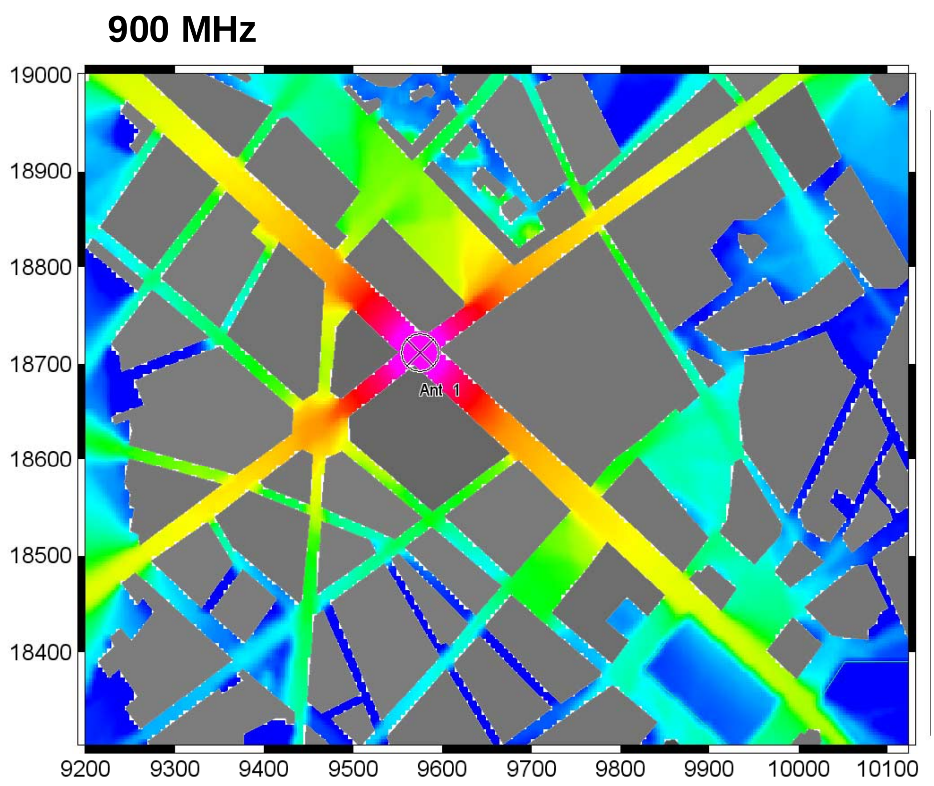


Fig. 2: **Urban propagation example @ 900 MHz carrier frequency**

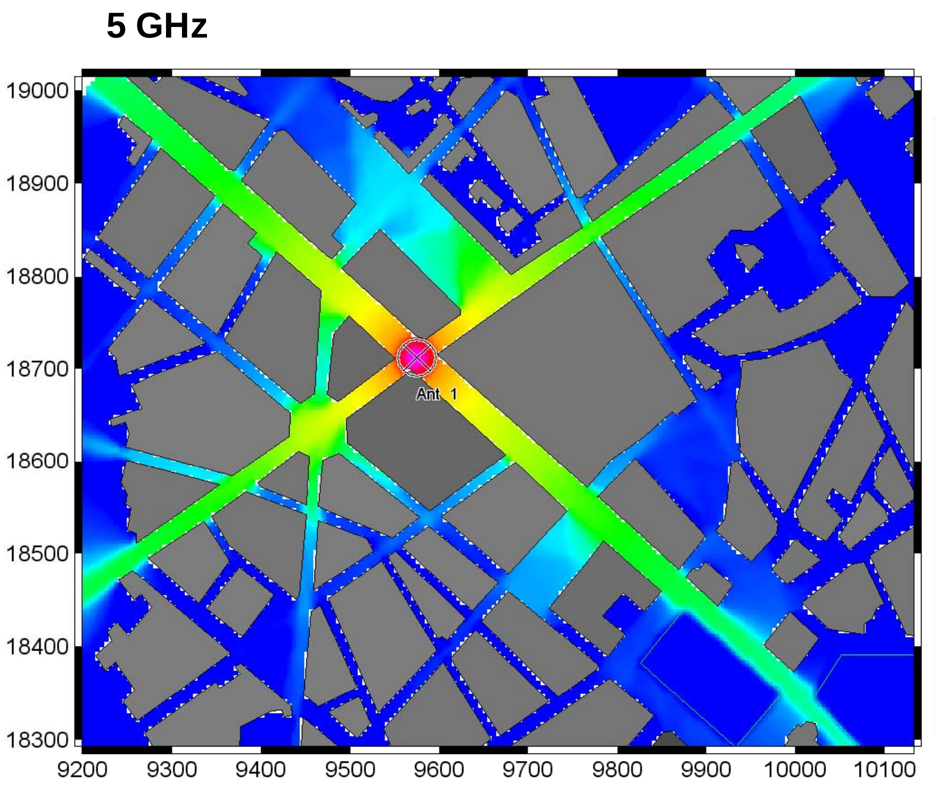


Fig. 3: **Urban propagation example @ 5 GHz carrier frequency**

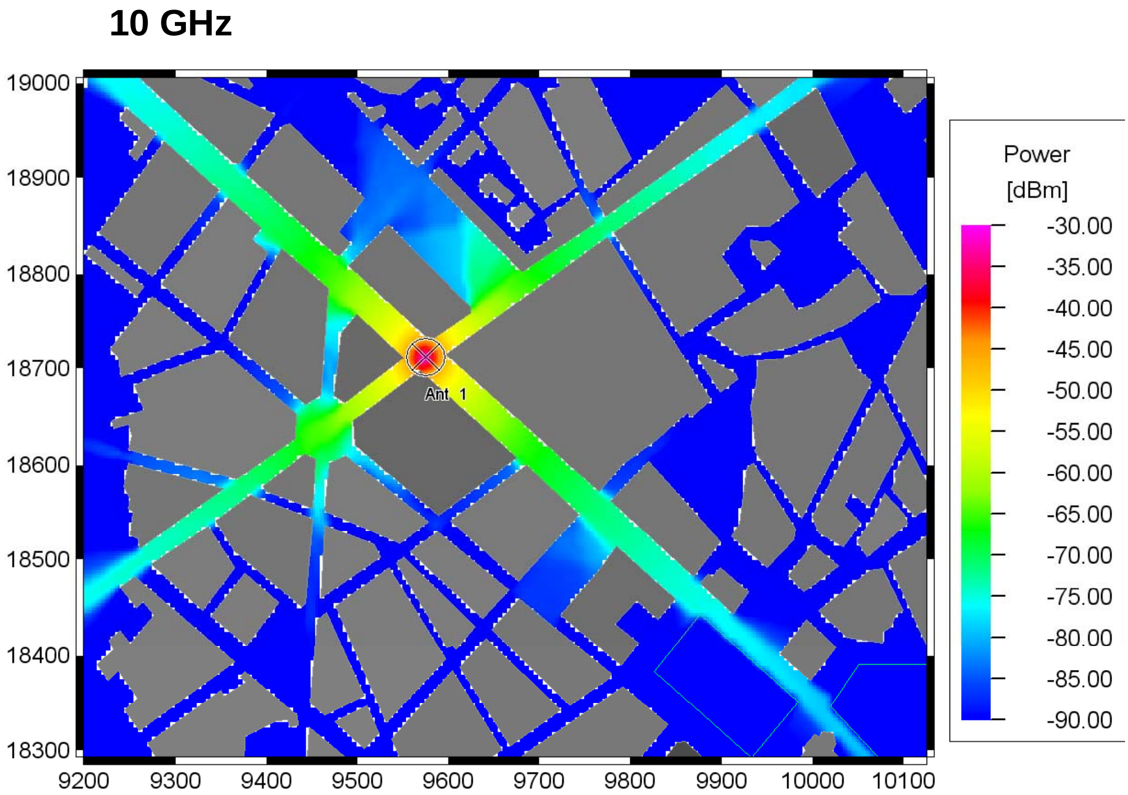


Fig. 4: **Urban propagation example @ 10 GHz carrier frequency**
(Figs. 2-4 courtesy to 'Institut für HF Technik, Universität Stuttgart, Dipl. Ing. P. Wertz', simulation based on ProMAN, AWE Communications, Gärtringen)

Within the coverage areas shown above, the link between transmitter and receiver (called radio or propagation channel) normally is complex and strongly varies over time. In contrast to a LOS channel which is relatively stable for MAN scenarios, NLOS receivers have to cope with a series of signals due to multiple propagation paths arriving from different directions with different amplitudes, phases and delays. These effects are even more restrictive if in-building coverage (the really interesting case) is considered. All these effects are not new and well known from mobile cellular systems. Mathematically, such a transmission channel can be modelled by a transmission filter which is not flat in the transmission band but shows strong variations and deep notches (resulting in intersymbol interferences and frequency-selective fading), and additionally all this has a dynamic (time-variant) behaviour.

In Figures 5 to 7 the channel transfer function is shown for typical LOS and NLOS channels according to sounding measurements at 3.5 GHz. The measurements show the amplitudes of the transmission channel (Z-Axis) over the frequency deviation from the carrier frequency (X-Axis) for a number of snapshots at different times (Y-Axis). While the LOS channel (Fig. 5) shows a relatively undistorted transmission function, that is fairly stable over time, the OLOS channel (Fig. 6) already is much more distorted in the frequency and time domain. This behaviour getting worse for the NLOS channel (Fig. 7) where the principle behaviour is the same but with stronger variations in frequency and time. The period of such variations is approximately represented by the coherence frequency and coherence time.

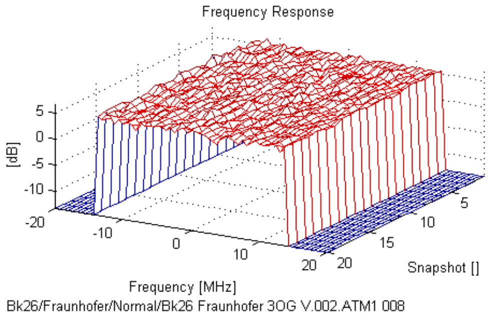


Fig. 5: **Channel transfer function @ 3.5 GHz for LOS**

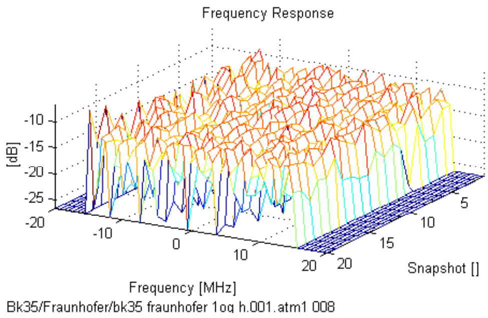


Fig. 6: **Channel transfer function @ 3.5 GHz for obstructed LOS (trees)**

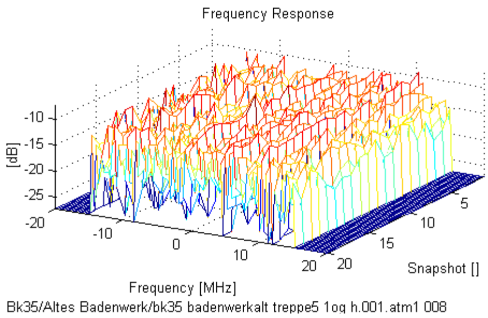


Fig. 7: **Channel transfer function @ 3.5 GHz for NLOS (outdoor)**

In case of broadband single-carrier transmission (typically combined with TDMA, Time Division Multiple Access) severe distortions (and thus intersymbol interferences) will occur if the signal bandwidth is larger or equal to the coherence frequency (i.e. to the transfer function variations over frequency). This can lead to a complete loss of the transmitted signal if the receiver can no longer demodulate the received signal correctly. Some countermeasures are possible with powerful time domain equalisers able to compensate for some distortion.

For medium data rate transmission (like UMTS) an alternative is given by the W-CDMA (Wideband Code Division Multiple Access) technique. Here, the data signal is not directly modulated onto a single carrier but multiplied before with a pseudo-random data sequence in such a way that the resulting signal is spread over a wider bandwidth up to the full channel bandwidth. In the receiver, the signal is restored via the known correlation properties of the pseudo-random data sequence. Any spreading makes the signal less vulnerable to narrowband time-varying channel distortions in particular due to the effect that the multiple access is now performed in code instead of time domain. As a macroscopic result, degradation due to the channel imperfections generally is more smooth as in the case of a non-spreaded signal.

Nevertheless, the amount of spreading is constrained as the data rate is intended to be fairly high and the overall bandwidth normally is limited. Therefore, alternative solutions using OFDM (see below) have been investigated and applied for applications like DAB (Digital Audio Broadcast) and DVB-T (Digital Video Broadcast Terrestrical) where the requirements are similar (transmission of broadband signals through strongly distorted and time-variant channels). OFDM(A) means Orthogonal Frequency Division Multiple (Access) and is based on multi-carrier transmission with a very high number of orthogonal carriers where typical examples are 256, 1024 or 2048 carriers. The broadband data signal is split into as many parallel data streams as carriers exist, any carrier can be individually and dynamically optimised in terms of the modulation scheme (dynamic adaptive modulation) and some other transmission parameters in order to have the maximum amount of degrees of freedom for optimisation. Although the technology and the associated implementation in detail are quite complex, it is easy to understand that such a flexible approach is well suited for transmission channels as described above.

In addition to DAB and DVB-T, some wireless standards are using this approach in different versions. IEEE 802.11a,g (Wireless LAN) is already commercially available, IEEE 802.16-2004 and IEEE 802.16e are going to use it and there are also a couple of proprietary solutions working with variants of the technology. ADSL technology is also based on OFDM or variants like DMT (Discrete MultiTone).

As compared to the basic versions of W-CDMA, OFDM is going to use higher order (adaptive) modulation schemes like 16-QAM or even 64-QAM. This is a theoretical advantage in terms of spectrum efficiency. Nevertheless, in practical situations, the carrier to noise and interference ratio is not always good enough to really utilise that advantage. In particular, in difficult NLOS situations (like in-building coverage) the system has to switch back to the most robust scheme (BPSK or QPSK) which is the same as in the W-CDMA case (QPSK) or even worse. Consequently, OFDM can show relatively good performance for LOS or OLOS situations but will not perform significantly better than W-CDMA in cases where strong NLOS conditions occurs.

OFDM is also limited in case of fast flat fading and also needs some spreading over time for maximum performance, usually achieved by error-control coding. In summary, the OFDM performance (as well as for single-carrier transmission and W-CDMA) depends on a multitude of conditions and this is the main reason for the big number of conflicting statements that have been published. It is therefore extremely important to understand the performance limits of the technology in the different environments.

In particular, comparing WiMAX to UMTS, WiMAX can deliver more bandwidth and coverage in the LOS case but in the OLOS and NLOS case this is no longer true. On top of that, there will be enhanced versions of UMTS like HSDPA (High Speed Downlink Packet Access) using 16-QAM modulation and enhanced uplink schemes, improving the performance of UMTS considerably beyond data rates as known from today's implementations typically offering a maximum of 384 kbit/s. Another interesting approach is TD-CDMA, where the TDD UMTS air interface is used in licensed frequency bands other than for mobile systems (e.g. 2.6 GHz) for fixed access.

In addition to the coverage and coverage related throughput effects described above, there are additional limitations in some cases which relate to frequency and bandwidth availability. In contrast to 2G and 3G mobile systems, no global frequency allocation for WiMAX systems still exists. Frequency bands of interest today mainly comprise the 3.5 GHz band (TDD or FDD allocations), bands around 2.5 GHz (TDD allocations) and globally available unlicensed bands (e.g. 5.8 GHz). Looking at the licensed bands with a sufficient potential of QoS, the available bands at 2.5 GHz and 3.5 GHz do not offer large channel bandwidths. Furthermore, for a real world deployment, self-interference inevitably present in large multi-cellular systems has to be considered since this leads to further bandwidth demands for re-use frequency purposes.

The available channel bandwidth (usual examples are 3.5, 7, 14 and sometimes 20 MHz) per sector in a PMP (Point-to-MultiPoint) architecture has to be considered as a resource that all users in a sector have to share. Consequently, the resulting data rate per user (either committed or uncommitted) strongly depends on the actual traffic situation in a sector and the QoS requirements per terminal. For a rough calculation, the following modulation efficiencies and associated shared resource data rates can be assumed:

Application	Spectral efficiency [Bit/s/Hz]	Shared resource (total data rate per sector [Mbit/s])		
		3.5 MHz channel	7 MHz channel	14 MHz channel
LOS	2 - 3	7 - 10	14 - 20	28 - 40
OLOS	1 - 2	3 - 7	7 - 14	14 - 28
NLOS	< 1	< 3.5	< 7	< 14

Table 3: Expected shared resource data rate (@ 3.5 GHz band including propagation and multi-cellular effects

For large effective user data rates, a considerable amount of oversubscription has to be assumed in order to compete with DSL solutions. This again depends on the user application. For usual web browsing of an individual subscriber including a certain activity factor (not all users subscribing to flat rates), oversubscription rates can be fairly high (10 – 20), whereas for more demanding customers or streaming multimedia content this assumption is no longer true.

- **Now, what can we get in Reality ?**

Table 4 summarises a set of performance parameters for some air interface standards, assuming normal (neither best- nor worst-case) conditions, where the lower right column is an exception showing the influence of regulatory constraints on the PFD (Power Flux Density).

As a result, LOS applications with sufficient bandwidth normally offer a superb performance but require some effort for installation where NLOS applications (the interesting case for residential access) are quite limited aiming at self-installation. It should be noted that the figures from Table 4 can only be seen as a rough assessment for comparison.

Standard	Transmission channel or medium	Maximum theoretical user data rate [Mbit/s]	Effective user data rate under normal conditions [Mbit/s]
WiFi (IEEE 802.11g) @ 2.4 GHz	Radio indoor	54	20 – 25
UMTS (W-CDMA) @ 1.9 GHz	Radio NLOS	2.8	0.2 - 0.3
UMTS (HSDPA) @ 2.2 GHz	Radio NLOS	14	1
UMTS TD-CDMA @ 2.6 GHz	Radio NLOS	3	0.6 - 0.7
WiMAX (fixed) @ 3.5 GHz @ 20 MHz bandwidth	Radio LOS	80	14 – 20
WiMAX (fixed) @ 3.5 GHz @ 20 MHz bandwidth	Radio NLOS	20	2 – 4
ETSI BRAN HiperAccess (> 10 GHz) @ 28 MHz bandwidth	Radio LOS	120	20 – 30
ADSL	Copper	4 - 6	3 – 4

Standard	Transmission channel or medium	Maximum link range (normal conditions) [km]	Worst case link range under PFD constraints [km]
WiFi (IEEE 802.11g) @ 2.4 GHz	Radio indoor	< 0.1	< 0.1
UMTS (W-CDMA) @ 1.9 GHz	Radio NLOS	5 - 10	5 – 10
UMTS (HSDPA) @ 2.2 GHz	Radio NLOS	1 - 2	1 – 2
UMTS TD-CDMA @ 2.6 GHz	Radio NLOS	2 - 3	2 – 3
WiMAX (IEEE 802.16d) @ 3.5 GHz.	Radio LOS	20	< 5
WiMAX (IEEE 802.16d) @ 3.5 GHz.	Radio NLOS	2 - 3	< 1
ETSI BRAN > 10 GHz @...	Radio LOS	40 (12 for PMP)	5
ADSL	Copper	4 – 5	n.a.

Table 4: Comparison of different air interface standards with ADSL (assuming sufficient bandwidth resources, normal propagation conditions and PMP operation with an average system load and reasonable traffic conditions)

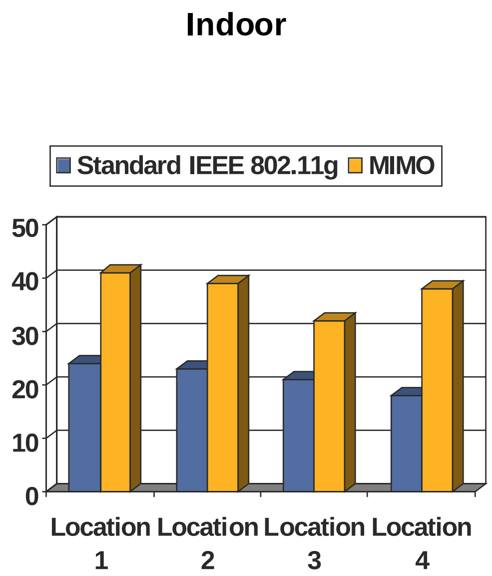
All these considerations are of importance for business case calculations. Due to the large number of boundary conditions and their impact on the performance, simple rules can not be given. On the other side, there is no clear winner that clearly outperforms all other standards as some aggressive marketing and advertising statements may suggest. In practice, running a broadband fixed wireless business case scenario, the more general aspects described above have to be mapped onto the individual constraints of the actual situation.

- **Is there any possibility for improvement ?**

As pointed out, the determining parameters for a commercially attractive broadband wireless access solution are the resulting user bandwidth with a certain QoS and in particular the coverage. Efficient adaptation of the transmission scheme to the complex radio channel is the key area for further improvement. While most of the activities centered around modulation, channel coding and multiple access schemes, other important influence factors had been neglected.

One of the important areas is the antenna technology used. Today’s systems usually utilise relatively simple and passive antenna concepts. This is mainly due to the effect that such antennas have to be compatible with compact and easy to use equipment. Modern research activities, nevertheless, have shown that compact multiple antennas on both sides of the transmission path can substantially improve parameters that are directly visible to the user. Technologies of that kind are usually referred to as MIMO (Multiple In Multiple Out). Based on MIMO transmission, spectral efficiency, coverage and link budget can be optimised at the same time. The method is particularly efficient in the case of rich scattering which typically occurs for NLOS channels. MIMO technology is able to constructively use the information transmitted over the different paths. Using multiple antennas at the central station of a radio access system is straightforward, however, the implementation in a subscriber device (like laptop, PCMCIA cards, etc.) is a challenge. But latest products in that area demonstrate the feasibility of the approach.

As an example, recent innovation steps in the WLAN area using MIMO demonstrate astonishing improvements. Even with a low number of MIMO paths (three in the example shown), bandwidth and coverage are substantially better as compared to a conventional system. As a consequence, it is planned to implement MIMO technology into future WiMAX systems as well.



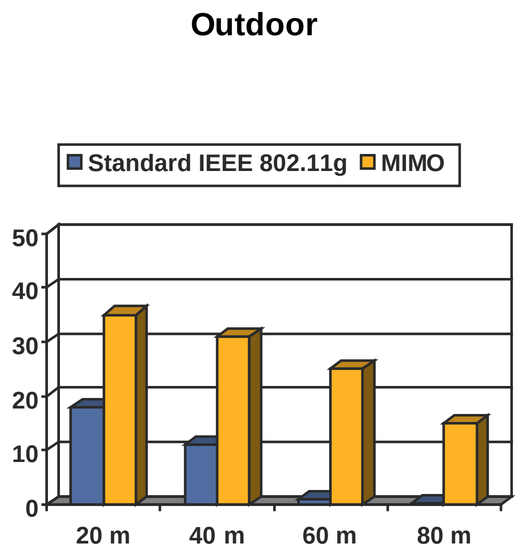


Fig 8: Performance comparison of a conventional WLAN system with a MIMO WLAN (Measured throughput in Mbit/s as a function of location)

Such technologies are able to improve the parameters shown in table 4 in a similar way as demonstrated for the WLAN example. Fortunately, enhanced antenna technologies are widely independent from the core air interface technology and can implemented in a further step, if the higher performance is required. As a compromise, more simple technologies might also be of interest as long as they are not incompatible with the interoperability requirement. A promising candidate in that respect is polarisation diversity at the base station and/or the user teminal.

➢ Marconi Strategy and Product Portfolio

Comparing the different scenarios for high and low frequencies shown in Table 4, the best combination is a hybrid solution featuring:

- a high performance air interface optimised for LOS applications like ETSI BRAN HiperAccess combined
- together with an air interface standard suited for NLOS coverage like WiMAX.

As a consequence, the Marconi AXR available today and focusing on LOS frequency bands above 10 GHz will be extended by a WiMAX air interface in particular at the base station side. The LOS solution provides full carrier class QoS to demanding customers and/or cellular systems (2G, 3G or similar), the additional WiMAX air interface operated at lower frequencies is intended to serve mainly residential customers with less demanding parameters. In the case of global WiMAX availability, CPEs will be a commodity or integrated into usual end user devices (like laptops) as WLAN today.

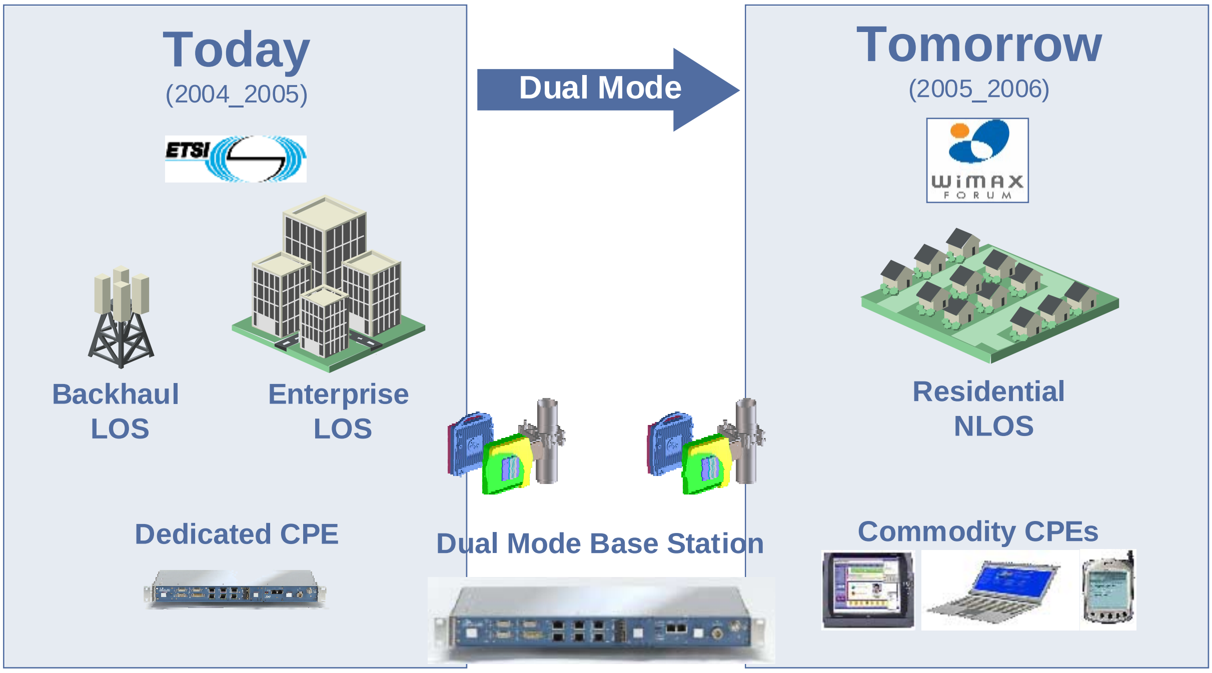


Fig 9: Marconi AXR and its migration to WiMAX