Efficient Multiple Access Schemes for Wireless Broadband Point-To-Multipoint Access Networks

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Abstract

The standardization of broadband wireless access (BWA) systems is currently in progress in different standardization bodies around the world. BWA systems are connected to different core networks and should support various services, where the basic radio physical layer should be independent of the core network. The maximum data rate per user should be 25 Mbit/s, at least for the downlink direction from the base station to the terminals, with a quality of service comparable to wireline technologies.

Broadband access systems with a point-to-multipoint architecture (PMP) allow high peak data rates per user in conjunction with high statistical multiplex gains especially in case of traffic with high burstiness. A multiple access scheme based on TDMA outperforms other potential access schemes like CDMA and OFDMA with respect to data rate flexibility and efficient implementation. In order to achieve a large cell radius, a high transmit power in the terminals is required even in case of low user data rates, however, the power requirement can be relaxed by combining TDMA and FDMA, i.e. sub-channeling for the uplink direction. A dynamic allocation of the terminals to the subcarriers is required to maximize the statistical multiplex gain. It is also shown how this multiplex gain is related to the channel size.

1 Introduction

Several standardization bodies around the world consider broadband wireless access systems. In Europe, ETSI BRAN (Broadband Radio Access Networks) has started the work on the HiperAccess (High performance Access) project. BRAN addresses an interoperable standard with a common air-interface. Main driving forces for HiperAccess include the convergence of speech and data services, the de-regulation of the markets and the current allocation of radio frequencies in many European countries.

The wireless access system with a PMP (Point-to-MultiPoint) architecture as illustrated in Figure 1 can be connected to different core networks via the access hub and should support various services, e.g. switched traffic, burst data like IP and ATM and also broadband services like video-on-demand. The basic radio physical layer should be independent of the core network by means of appropriate adaptations in the DLC (data link control) layer. Links exist only between the base station (BS) and the terminals stations (TS) and there is no peer-to-peer communication between terminals.

The transceivers consist of the digital modem, the IF (Intermediate Frequency) and the RF (Radio Frequency) units. The DLC block has the organization task of the multiple access scheme in conjunction with the radio resource manager and the CAC (Call Admission Control). The base station transmits in the downlink direction in a broadcast-manner to all terminals, i.e. all terminals receive and demodulate this signal and extract only their dedicated part after decoding. For the uplink direction, the common spectrum resource must be shared between the terminals by means of an appropriate multiple access scheme, which is discussed in detail in Section 3.

Generally, the PMP system and the multiple access scheme should be designed in order to achieve

- high flexibility in data rates and services,
- a maximum data rate per user of 25 Mbit/s, at least for the downlink direction from BS to TS,
- a quality of service comparable to wireline technologies like xDSL,
- maximum spectral efficiency and high statistical multiplex gains especially in case of traffic with high burstiness,
- efficient implementation.

Given these requirements, we will see in Section 3 that a TDMA (Time Division Multiple Access) scheme beats other potential access schemes like CDMA (Code Division Multiple Access) and OFDMA (Orthogonal Frequency Division Multiple Access).

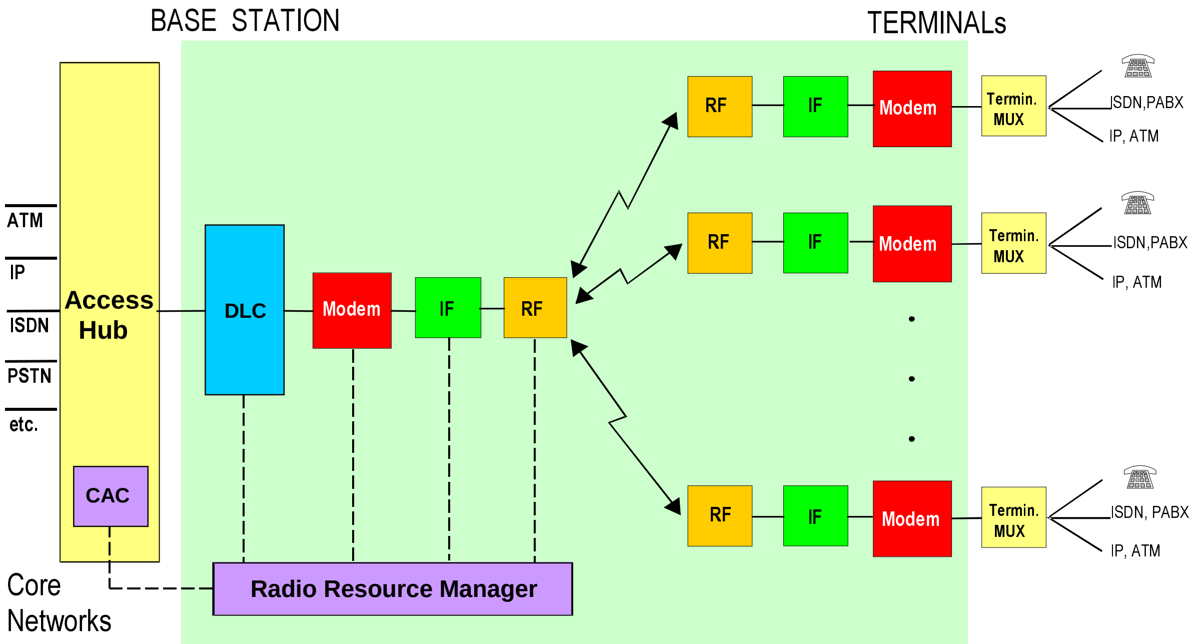

Figure 1: PMP architecture

In order to achieve a large cell radius, a high transmit power in the terminals is required even in case of low user data rates. However, the power requirements can be relaxed by combining TDMA and FDMA (Frequency Division Multiple Access), i.e. by sub-channeling for the uplink direction. A dynamic allocation of the terminals to the subcarriers is required to maximize the statistical multiplex gain and the spectrum utilization. It is also shown in Section 4 how this multiplex gain is related to the channel size which provides a criterion for the specification of the channel size and the channelization plan.

2 Frequency Allocations and Link Budget

Various frequency ranges are foreseen to accommodate wireless access networks: low frequencies of 3.5 GHz offer some advantages but spectrum is hardly available, high frequencies at the 26, 28 or 32 GHz range are currently the most important candidates (with carrier bandwidths of 28 MHz), and very high frequencies of 42 GHz are mainly addressed by BRAN. The BRAN project shall also support an allocation of about 1 or 2 GHz spectrum in the 42 GHz range by the relevant standardization bodies. For all frequency ranges, line-of-sight connections between the base station antenna and the terminal antennas are required. The characteristics of the radio channel depend strongly on the frequency range as summarized in Table 1.

Criterion	low frequencies (e.g. 3.5 GHz)	high frequencies (e.g. 26, 32, 42 GHz)
Spectrum availability	already occupied	about 2 GHz will be available
Radio channel characteristics		
• ISI	ISI possible	ISI usually negligible
• rain fading	no rain fading	severe rain fading (depending on distance and availability)
Cell radius	large (10...15 km)	small (2...5 km)
Costs of feeder network	low (can adapt to user density)	high
Costs of customer premises equipment (CPE)	low	high (frequency generation, power amplifier)

Table 1: Comparison of frequency ranges

The radio channel could be characterized by intersymbol-interference (ISI) due to multipath propagation and additional flat fading during periods of heavy rain. ISI is not the main challenge if there are no obstructions (e.g. trees) in the first Fresnel zone of the line-of-sight link. The problem of multipath propagation generally relaxes with higher frequency ranges, since all reflections will be more diffuse with smaller wavelengths. The rain fading is the more important effect for wireless access at high frequency ranges, since it has major impact on the link budget. The required transmit power P_{TX} is calculated in decibels as

$$P_{TX} = a_{pathloss} + P_{noise} - G_{TX} - G_{RX} + a_{rain} + L_0 + C/N$$

where

- $a_{pathloss} = 20 \cdot \log(4\pi f_c d / c)$ is the line-of-sight pathloss (characterized by an increase of 6 dB for doubling the distance) where d = distance and f_c = carrier frequency,
- $P_{noise} = FKTB$ is the noise power where F = receiver noise figure, K = Boltzman constant, T = temperature and B = bandwidth,
- G denotes the antenna gains for transmitter and receiver stations,
- C/N is the required carrier-to-noise ratio depending on the modulation and coding scheme,
- L_0 represents implementation losses (interference margin, tolerance, radom attenuation),
- a_{rain} is the rain attenuation, which increases *approximately* by a fixed amount in dB per km, but the *exact* relations are more difficult [1, 2]. Anyway, the rain fading can cause severe degradation at high frequency ranges, depending also on the required availability, the rain zone and the type of polarization.

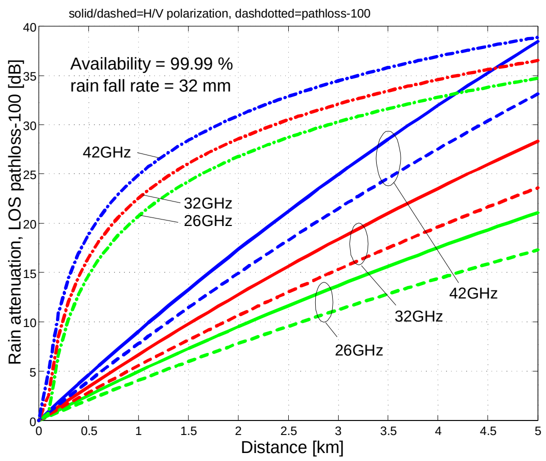

Figure 2: Rain fading @ availability=99.99% and free-space loss (depending on the frequency range)

The rain attenuation and the free-space pathloss are compared in Figure 2. For the rain fading a link availability of 99.99% is assumed, i.e. only in 0.01% of time per year (corresponding to about 1 hour per year) the fading due to heavy rain exceeds the presented attenuation. It should be noted that an increase of the availability from 99.99% to 99.999% implies approximately a doubling of the rain fading. The rainfall rate of 32 mm/h corresponds to rain zone H [4]. For low frequency ranges, e.g. 3.5 GHz, the rain fading is limited to 1 or 2 dB only and thus negligible at all. There is a cross-over distance definable at about 1.5 to 2 km, i.e. below that distance the free-space-loss curve is steeper than the rain fading curve and vice versa above the cross-over distance.

Figure 3 shows the required transmit power for several types of terminal antennas and additionally for horizontal and vertical polarizations. The base station is assumed with 45 degree sectorization (8 sectors) and 17 dBi antenna gain. The terminal antenna gains are 28 dBi, 35 dBi and 41 dBi for the planar, the 30 cm and the 60 cm parabolic antenna, respectively. Further parameters are a receiver noise figure of 8 dB, an offset of 7 dB (can be reduced to 3 or 4 dB if the interference from adjacent cells is considered explicitly [10]) and a required C/N of 7 dB (depending in detail on the modulation and coding scheme [10]).

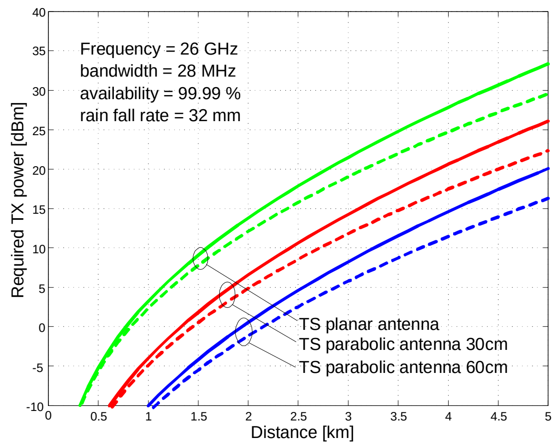

Figure 3: Required transmit power @ 26 GHz (depending on the terminal antenna type)

For realistic terminal transmit powers of about 20 to 25 dBm the maximum range is typically between 2.5 km and 4.0 km as a conclusion from Figure 3. For higher frequency ranges or higher availability, the range will be considerably reduced.

Two further limitations on the maximum transmit power have to be considered. Firstly, the power flux density (PFD) is limited to 10 and 50 W/m2 for normal and professional people, respectively [3]. The resulting maximum permitted transmit powers are summarized in Table 2. Secondly, there must be a minimum safety distance to guarantee the maximum permitted PFD, which is reported in Table 3.

Antenna type	PFD = 10 W/m2	PFD = 50 W/m2
planar	17.5	24.5
parabolic, 30 cm	22.5	29.5
parabolic, 60 cm	28.5	35.5

Table 2: Maximum permitted TX power [dBm]

Antenna type	P_{TX} = 20 dBm	P_{TX} = 25 dBm	P_{TX} = 30 dBm
planar	0.7	1.3	2.2
parabolic, 30 cm	1.4	2.5	4.5
parabolic, 60 cm	2.8	5.0	8.9

Table 3: Safety distance [m] for a power flux density of 10 W/m2

Due to their great required safety distance, the 60 cm parabolic antennas are only suited for certain applications. Hence large parabolic antennas at the terminal side are not the general solution to save transmit power for the uplink direction. As the main conclusion, the physical layer (especially modulation and coding) and the multiple access scheme should be designed for power efficiency.

3 Multiple Access Schemes for Wireless PMP Systems

The wireless access system with a PMP architecture is illustrated in Figure 1. It was already mentioned in Section 1, that the common spectrum resource must be shared between the terminals in the uplink by means of an appropriate multiple access scheme. Candidates for multiple access schemes are listed in Table 4: FDMA (Frequency Division Multiple Access) [5], TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access) [6] refer to separation by frequency, time and code sequences, respectively. For OFDMA (Orthogonal Frequency Division Multiple Access) [7], a terminal transmits in the uplink direction on some OFDM subcarriers and the subcarriers of different terminals must appear as orthogonal at the base station.

Another means of separation could be SDMA with antenna beamforming. However, it should be noted that SDMA raises a lot of questions ranging from spectral efficiencies to details of the DLC layer and implementation issues demanding for further research. The sectorization of cells could be addressed as a specific subset of static fixed SDMA. Finally, polarization implies two orthogonal signal spaces and allows sharing of spectrum between adjacent cells or sectors.

CDMA is most suitable for voice applications but not for peak data rates where a single terminal occupies the complete spectrum of a sector. The feature of graceful quality degradation of CDMA is not advantageous and severe ISI is not present at all. Furthermore, CDMA and also OFDMA have high crest factors and require more backoff (for the downlink). Power control in the uplink is required especially for CDMA. Considering OFDMA it seems questionable to guarantee nearly perfect orthogonality between the received subcarriers of different terminals.

As a conclusion from Table 4, FDMA and TDMA seem to be the best candidates for wireless access. The main advantages of FDMA are the low transmit power requirements, the simple implementation and the possibility to use only parts of the 28 MHz band within the sector to ease the frequency and cell planning. A drawback of FDMA is the inflexibility to adapt to fast data rate changes (requiring fast changes in the baud rate) and for burst data transmission (requiring fast setup and release of carriers). Additionally, synchronization is a difficult issue for the combination of very low data rates with narrow carriers and high carrier frequencies. TDMA is best suited for burst data traffic and performs for low as well as for high data rates. TDMA for the uplink direction and TDM for the downlink means that the base station transmits a stream of data packets corresponding to time slots within a frame structure, and the terminals have access grants to dedicated time slots in the uplink direction, where a data packet may contain one ATM cell. However, the only major drawback of TDMA is the high required terminal transmit power, even if the data rates of the terminal are currently or always low. This could be relaxed by a hybrid combination of FDMA and TDMA for the uplink direction only, i.e. the terminal transmits not only in specific time slots but also in specific frequency slots (being identical to subcarriers).

Criterium	FDMA	TDMA	async CDMA	sync CDMA	OFDMA
Suitable for burst data, variable bit rate, high statistical. multiplex gain	burst data not possible, variable bit rate delayed	packet and slots could be associated	most suitable for voice applications or CBR services		
High data rates			requires broad bands		
Low data rates	sync difficult		best performance, but graceful degradation undesired		requires many subcarriers
Symbol delay	frame relevant				frame relevant
Flexible bandwidth per sector	use part of channel				use only some subcarriers
Spectrum efficiency			inefficient, even for reuse 1		
Reference system gain, frequency reuse			system must be designed for full data rates: no Rx sensitivity benefit		backoff
Robustness to channel impairments (ISI), but not a major problem due to LOS	depends on subcarrier size	more sensitive			
Robustness to interference			reuse 1 possible		
Transmit power required		high, even for low data rates			
Implementation			UL power control	UL power control, synchronization,	orthog. loss, high backoff
Maturity					acad. research

Legend: excellent | fair | poor

Table 4: Comparison of multiple access schemes (for uplink)

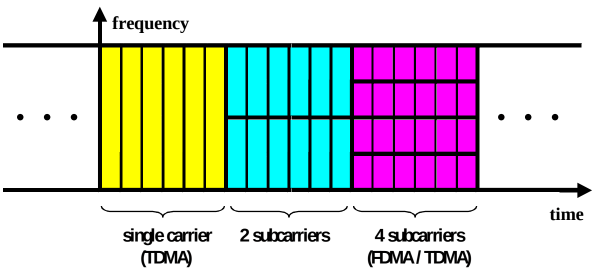

Figure 4: Hybrid TDMA/FDMA multiple access scheme for the uplink

In Figure 4 a hybrid TDMA/FDMA scheme is illustrated [11], where different modes of operation with a single carrier or with 2 or 4 subcarriers on different time subframes are presupposed to allow for different types of terminals. With four subcarriers the required transmit power is reduced by 6 dB and the peak data rate per terminal is reduced by a factor of four. However, a reduction of the system capacity will not occur, if the terminals are dynamically allocated to the subcarriers, otherwise a fixed allocation will reduce the statistical multiplex gain of the access system (see next Section).

4 Statistical Multiplex Gain

A PMP system for burst data services (IP, ATM) performs like a virtual multiplexer. Let r_s be the total sector rate, r_p the peak data rate per user, r_a the average data rate per user, and $b = r_p / r_a$ the burstiness of the data source. For a static collision-free allocation of resources, only $N_{cf} = r_s / r_p$ user can be served within a sector. Due to the statistical multiplexing, the traffic peaks on all user data streams will usually not coincide, so more than N_{cf} users can be served if $b > 1$. Let N_{eff} be the effective maximum number of users (which are multiplexed together) under the condition that the required capacity $N_{eff}\, r_p$ exceeds the true capacity r_s of the sector only with a small probability (see below for an exact definition of the term "exceeding" based on the cell loss rate). The statistical multiplex gain G is defined as [8]

$$G = \frac{N_{eff}}{N_{cf}} = \frac{\text{max \# users with statistical multiplex}}{\text{max \# users with static collisionfree multiplex}}$$

$$= \frac{N_{eff} \cdot r_p}{r_s} = \frac{\text{required total sector rate with static collisionfree multiplex}}{\text{required total sector rate with statistical multiplex}}$$

Another important parameter is the spectrum utilization $U = G/b$ (also called spectral efficiency). The multiplex gain is defined with respect to the cell loss rate (CLR), which is the probability that cells can not be transmitted on time due to overload:

$$CLR = \frac{\text{average number of lost cells}}{\text{average total number of cells to be transmitted}}$$

$$= 1 - \frac{1}{r_a / r_s \cdot N_{eff}} \cdot \sum_{k < N_{cf}} (k - N_{cf}) \cdot \binom{N_{eff}}{k} \cdot p^k (1-p)^{N_{eff}-k}.$$

The evaluation of the simple-looking CLR formula is numerically difficult. Assuming a typical cell loss rate of 10^{-6}, Figure 5 displays *exact* graphs for the spectrum utilization U over r_a / r_s for various values of the burstiness, whereas in most references [8, 9] only *approximations* are given. These approximations are displayed in Figure 5 as dotted curves to show the difference to the exact results.

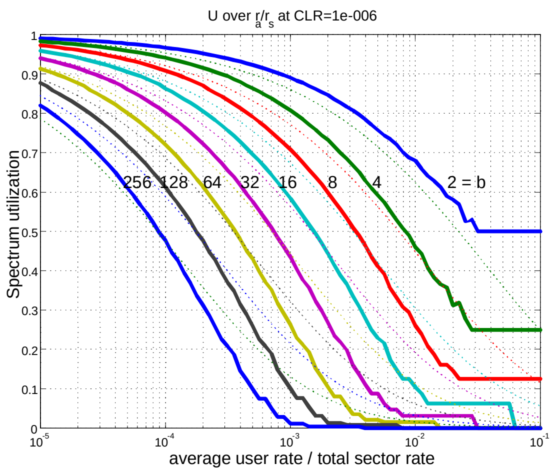

Figure 5: Spectrum utilization for a CLR of 10^{-6}

It can be shown that U approaches 1 for $r_a / r_s \to 0$ and U approaches $1/b$ for increasing r_a with $r_p = r_a b \le r_s$. It is a simple observation that the access system has a better spectral efficiency U with lower burstiness, but a better multiplex gain G with higher burstiness. However, the more interesting insights can be gained by horizontal instead of vertical comparisons within Figure 5. There are two important conclusions concerning the specification of reasonable bandwidths for PMP systems:

- High multiplex gain or high spectrum utilization requires a high number of users, i.e. a high bandwidth per sector and large sectors in order to achieve high user densities per sector. However, both large bandwidth as well as wide range imply an increase of the required transmit power in case of pure TDMA.
- The difference between poor and excellent spectrum utilization is approximately a factor of 10 to 100, depending on the burstiness and the r_a / r_s-value. Hence a doubling of the bandwidth per carrier has a certain but not overwhelming effect.

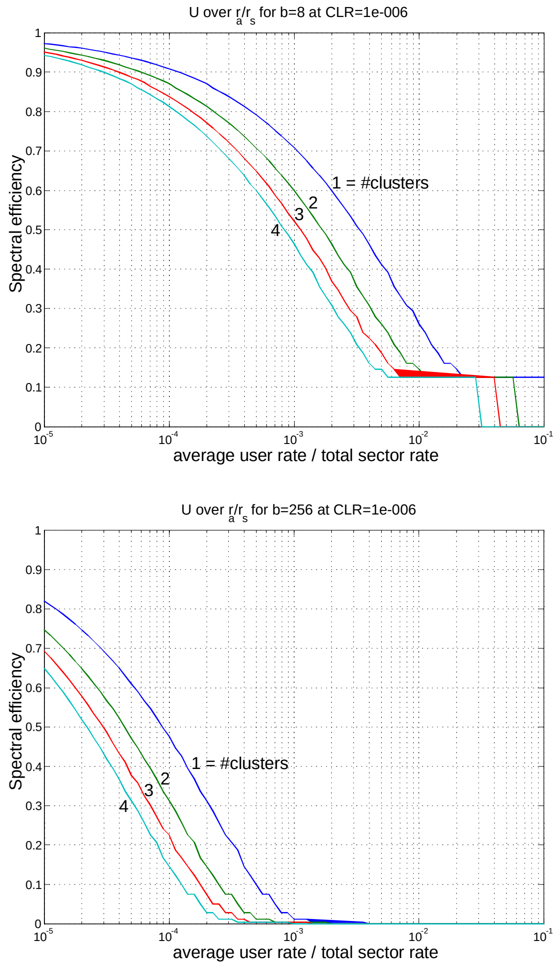

Figure 6: Spectral efficiency for b=8 (top) and b=256 (bottom) in case of user clustering

The statistical multiplex gain is considerably reduced as shown in Figure 6 if the terminals within a sector are allocated to fixed groups or clusters. Such a clustering occurs in the frequency-domain, if the allocation of terminals to subcarriers in case of hybrid TDMA/FDMA is static. However, a dynamic allocation to the subcarriers does not reduce the overall spectrum efficiency. Another example for clustering is the grouping of terminals in the time-domain to allow for longer block codes and interleaving in case of adaptive modulation and coding, see [10] for more details.

5 Conclusions

Wireless access networks require a high bandwidth per sector to achieve high statistical multiplex gains and high peak data rates per user. As a drawback of large channel sizes, the transmit power amplifier becomes more costly and the range reduces. The trade-offs between bandwidth, statistical multiplex gain, transmit power, coverage, frequency range, rain fading and availability have been analyzed. A bandwidth of 28 MHz seems to be a reasonable compromise. Given flexible data services and cost-effective implementation as the main design criteria, a multiple access scheme based on TDMA surpasses all other access schemes. A hybrid TDMA/FDMA scheme with dynamic allocation of terminals to subcarriers could allow transmit power savings at the expense of reduced peak data rates without loss of overall spectral efficiency.

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