# An Analysis of Code-Division Multiple Access for LMDS Networks

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## Abstract

The application of code-division multiple access (CDMA) to local multipoint distribution services (LMDS) networks is investigated with respect to interference minimization and to an optimum utilization of the bandwidth. Two basic approaches are presented for the downlink and the uplink. The first approach is derived from the frequency assignment scheme commonly used for time-division multiple access (TDMA). The second approach is based on the assignment of only one frequency per cell. In combination with cell sectoring done by narrow-beam subscriber antennas and a dynamic code allocation to the sectors, this method leads to a significant increase of the overall cell capacity and allows a more flexible cell arrangement. In addition, an extension of the second approach with multimode CDMA is introduced for the downlink which increases its worst case SIR. Finally, some implementation requirements are discussed.

## 1. Introduction

Broadband wireless access systems are expected to play an important role in the deregulated telecommunication market, especially for new operators having no wired infrastructure to reach the end users. The emerging local multipoint distribution services (LMDS) networks, which operate at millimeter-wave radio frequencies between 20 GHz and 45 GHz, have sufficient bandwidth to deliver integrated broadband services for business and residential subscribers. Nevertheless, bandwidth is a short resource, and therefore technical solutions for its optimum utilization are of great importance. One of the basic issues is the frequency reuse factor which determines the overall bandwidth needed in an LMDS network with a predetermined maximum cell capacity. Restrictions in using the available bandwidth in an optimum way arise from intracell and intercell interferences. There are two antagonistic requirements: The first is that the interference should be kept as small as possible, and the second is that each base station should serve as many subscribers as possible in its coverage area with a typical radius of 2-5 km.

With respect to the first requirement, LMDS networks employ narrowbeam directional subscriber antennas pointed to the serving base station. Compared with the use of omnidirectional antennas, this reduces interference from/to other cells and also increases the cell range for a given transmit power.

In addition to the use of such narrowbeam antennas, interference reduction and performance enhancement can also be obtained by cell sectoring as used in LMDS networks based on TDMA [1], [2]. Recently, code-division multiple access (CDMA) has become very popular in digital mobile radio systems [3], [4]. In this paper, we analyze the potential of CDMA to improve the quality of LMDS networks for both the downstream and the upstream channels.

Our considerations are based on the assumption (which is common in microwave and millimeter-wave radio systems with line-of-sight propagation) that the signal attenuation is proportional to the squared propagation distance.

For the application of CDMA, a two-layer concept is assumed, in which the transmitted signals are first spread by a Walsh-Hadamard sequence and then scrambled by a long pseudo-noise sequence. This scrambling makes adjacent cell signals look like noise. The Walsh-Hadamard spreading sequences form a set of orthogonal sequences (codes) without interference between different codes within the same cell. This approach is similar to that used in the IS-95 and the UMTS mobile radio standards.

Assignment of transmission capacity to the cells can be done in different ways. To be comparable, all approaches discussed in this paper are based on cell sectoring with 90° sectors. The base stations are arranged in a rectangular grid, where each cell around the base station is subdivided into four sectors.

Two LMDS network approaches are presented both for the downstream and the upstream links. In the first approach which is commonly used in TDMA systems, four frequencies are assigned to each cell, i.e., one to each sector. In the second approach, all sectors of a cell use the same frequency. A control algorithm is characterized for suppressing the intracell interference and increasing the number of subscribers. For the downlink, the intercell interference may cause that some subscribers located in an unfavorable area do not get any connection. To solve this problem, a multimode CDMA technique is suggested.

# 2. Downstream Link Approaches

## 2.1. Four Frequencies per Cell

We consider a rectangular cell pattern with four 90° sectors per cell, each occupying a bandwidth of W Hz. The CDMA spreading factor is N. As it has become popular in LMDS network design, different frequency channels are assigned to different sectors. The channels are labeled as A, B, C and D, respectively. Each of these channels is reused in adjacent cells by following the mirror-image rule of channel assignment **(Fig. 1)**. Because of this cell pattern, there is no intracell interference on one hand, and no interference between adjacent cells on the other hand. Most interference is due to the second-nearest cells which have an identical frequency arrangement, i.e., which use the four channels in the same directions. In the upper right part of Fig. 1 the interference situation is illustrated for a subscriber located at the border between sectors B and C; the interference is caused by the base station of the second nearest cell to the left.

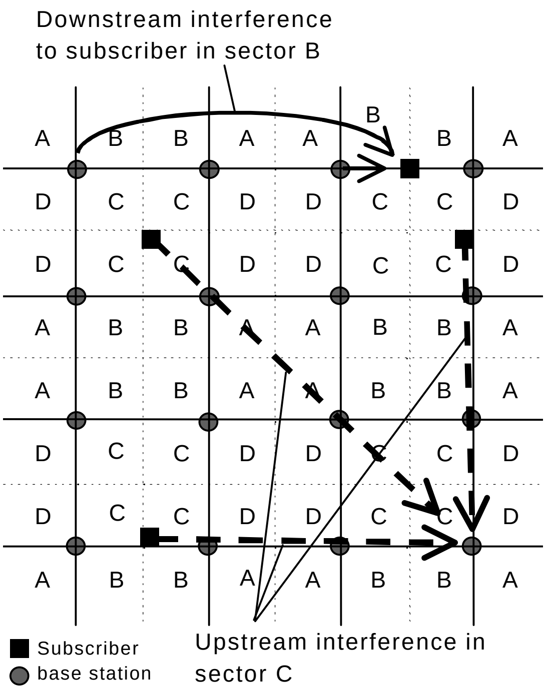


**Fig. 1: Rectangular cell pattern with 90° sectoring (A, B, C, D denote four different frequencies).**

The channel bandwidth is W Hz, and since the spreading factor is N, each code transmits a bit rate which can be transmitted in a W/N Hz bandwidth in the single-user case. The signal-to-interference-ratio (SIR) seen by a subscriber is given by

$$SIR(d) = 10\log\left[\frac{N}{K}\left(\frac{4D+d}{d}\right)^2\right] \text{ dB}, \qquad (1)$$

where K is the number of codes used by the base station, 2D is the distance between two adjacent base stations, and d is the distance between a subscriber and its base station (see [5]). The worst case SIR of 14 dB occurs when the subscriber is located at d = D, and K = N codes are active.

The SIR subjected to the subscriber’s position in a sector is shown in **Fig. 2**. Because of the equivalent cell configuration, there is no difference in the intercell interference and overall cell capacity between the CDMA and TDMA approaches.

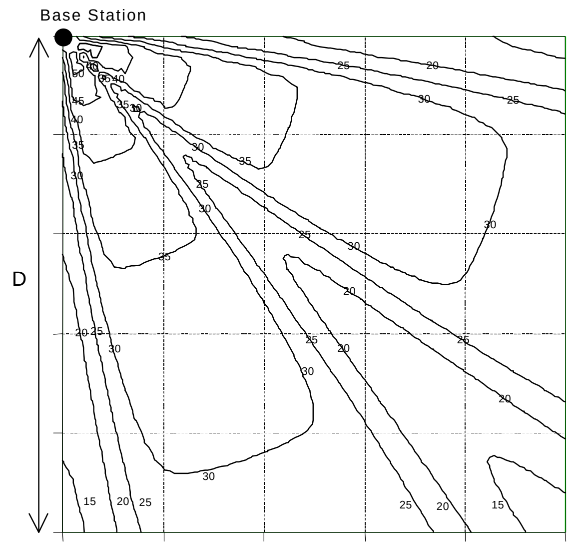


**Fig. 2: SIR distribution within a sector (subscriber antenna beam width 5°, base station in the upper left corner).**

## 2.2. One Frequency per Cell

The second approach aims at enhancing the overall cell capacity without increasing the intercell interference. Only one code family is reused in all sectors of the network. Again, a rectangular cell grid is assumed having four sectors per cell; all sectors of a cell use the same frequency. Four frequencies are assigned to the *cells* by observing the mirror image rule so that the intercell interference is mainly produced by the second nearest cells (**Fig. 3**). The worst-case SIR for this interference is 11 dB according to (1). The decrease from 14 dB to 11 dB is due to the fact that now two sectors interfere with N active codes each, i.e. K = 2N (see Fig. 3, upperleft sectors labeled as C). Additionally an intracell interference appears, because subscribers located along the sector borders receive two different downstreams on the same frequency. For example, the subscriber in the upper right corner in Fig. 3 will receive the downstreams which belong to both the upper and the lower sector C producing 0 dB worst-case SIR.

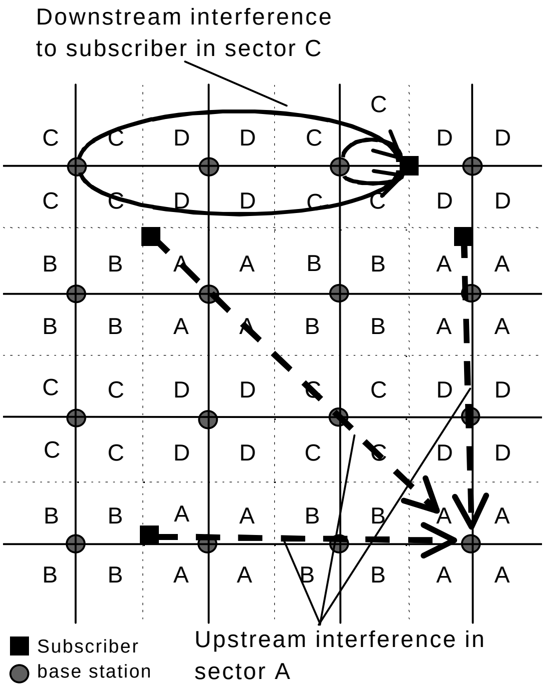


**Fig. 3: Rectangular cell pattern with 90° sectoring. A, B, C, D denote four different frequencies; all sectors in a cell use the same frequency.**

In order to overcome this problem, four overlapping areas and one non-overlapping area are introduced for each sector (**Fig. 4**). If, for example, in sector 1 the code set $\mathbf{N_1}$ is in use, a subscriber located in the non-overlapping area of sector 1 will receive only the codes from this set. A subscriber located in an overlapping area, however, will receive these codes plus the downstream codes belonging to its adjacent sector. To avoid overlapping effects, the base station must allocate downstream bandwidth in such a way that the conditions

$$\mathbf{N_S} \cup \mathbf{N_1} \subseteq \mathbf{N}$$
$$\mathbf{N_1} \cup \mathbf{N_2} \subseteq \mathbf{N}$$
$$\dots$$
$$\mathbf{N_{S-1}} \cup \mathbf{N_S} \subseteq \mathbf{N}$$

are always fulfilled. **N** is a CDMA code family, and $\mathbf{N_j}$ is the set of codes selected from **N** which are allocated to sector j; j = 1, 2, ..., S, where S is the number of sectors in a cell; S = 4 in our example. If the conditions above are fulfilled, then there is no intracell interference. Since the sectoring restricts in the overlapping areas the number of active codes to K = N, the intercell interference is again 14 dB (instead of 11 dB and K = 2N when no sectoring is performed).

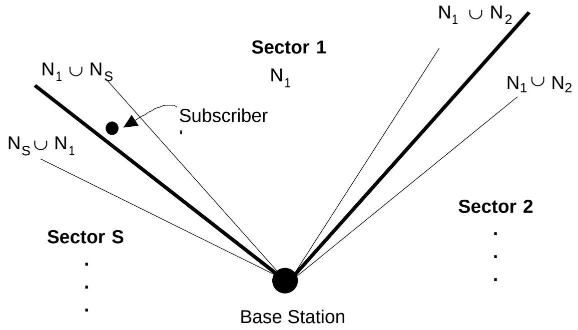


**Fig. 4: Downstream interference areas. In sector 1 there are two overlapping areas in which a subscriber receives code set $\mathbf{N_1} \cup \mathbf{N_S}$, or code set $\mathbf{N_1} \cup \mathbf{N_2}$, respectively.**

In applying this allocation procedure, a code used in one sector cannot be reused in neighboring sectors, and therefore in the downlink the maximum number of codes which can be used within a cell without any intracell interference is S*N/2. An advantage of this method arises from the fact that the overlap sector needs not to be located along the grid, but can be rotated towards regions with low subscriber densities. Also the number of sectors can be increased (with reduced antenna beamwidth). Note that the intercell interference remains unchanged although the available bandwidth in a cell increases with the number of its sectors.

## 2.3. Multimode CDMA

For the next method of CDMA application we likewise assume the usage of only one frequency within a cell, but now a spreading factor of 4N and a total bandwidth occupancy of 4W Hz is applied, where W Hz is the individual channel bandwidth. The set of 4N orthogonal spreading sequences of length 4N is partitioned into four disjoint subsets of N sequences, and each subset is assigned to one sector. Each sector can thus provide a capacity of N codes with a bit rate of W/N Hz per code. In terms of maximum cell capacity and bandwidth occupancy, this CDMA scheme is equivalent to the four frequencies per cell scheme for TDMA or CDMA. Since the bandwidth is 4W, all cells use the same frequency band and the distance to the interfering base station is reduced to 2D. Adjacent cells are separated only by the PN scrambling sequences in this case. The situation is shown in **Fig. 5** where A, B, C and D denote subsets of codes transmitted in the same frequency channel. With K designating the number of active codes, the SIR due to the adjacent cell is given by

$$SIR(d) = 10\log\left[\frac{4N}{K}\left(\frac{2D+d}{d}\right)^2\right] \text{ dB}, \qquad (2)$$

as derived in [5]. With K = 2N interfering codes and d = D, this leads to a worst case SIR of 12.5 dB, which is indeed worse compared with the four frequency per cell approach. This can be overcome by the multimode CDMA, which exploits the fact that only a small number of users are subjected to strong interference and that a particular processing can be adopted for these users located in the shaded regions depicted in **Fig. 6**. According to (2), the SIR at the inner edge (with d=0.7D) is 14.7 dB.

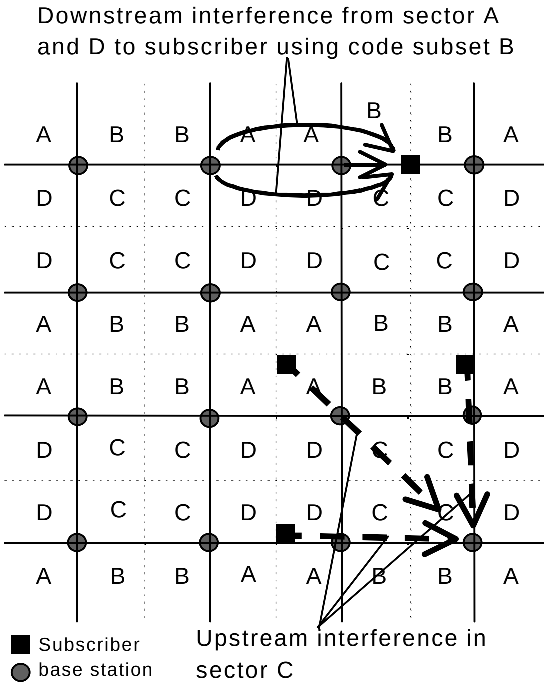


**Fig. 5: Rectangular cell pattern for multimode CDMA (A, B, C, D denote subsets of spreading sequences).**

To improve the SIR of users located in the shaded regions we extend the spreading sequence from 4N to 8N chips. With respect to the correlation over 4N chips the SIR is increased by 3 dB. Since the transmitted bit rate is reduced by a factor of two, just two sequences of length 8N have to be assigned to these users to keep the bit rate unchanged. From the family of scrambled Walsh-Hadamard codes these extended sequences, which do not destroy the orthogonality with the remaining length 4N sequences, can easily be constructed [6].

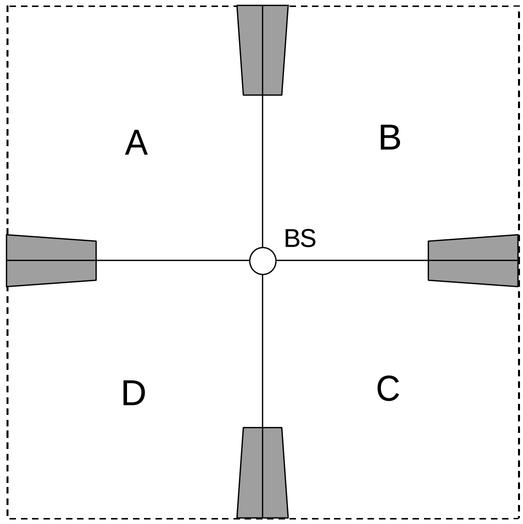


**Fig. 6: Strong interference regions on the downstream channel (shaded regions)**

In calculating the net gain in terms of worst case SIR, the increase of the total number of spreading sequences has to be taken into account. If M is the number of subscribers per sector to which double-length sequences are assigned, then the total number of sequences is N+M. The penalty associated to the increase of the number of sequences is:

$$P = 10\log\left(\frac{N+M}{N}\right) \text{dB}.$$

For M = N/8, this amounts to 0.5 dB, so that the net improvement of worst case SIR is

12.5 dB + 3 dB - 0.5 dB = 15 dB.

This concept can be generalized by defining an arbitrary number of areas in each sector and by assigning sequences with different lengths (e.g. 8N, 16N, ...) according to the interference in these areas [5].

# 3. Upstream Link Approaches

## 3.1. Four Frequencies per Cell

The cell pattern is the same as in case of the corresponding downstream link in Fig. 1. However, a base station may receive three different upstream beams on the same frequency sent by subscribers from second nearest cells, which are located in the horizontal, vertical or diagonal directions, respectively. The interference paths are indicated by the dashed lines in Fig. 1. Assuming that all these subscribers use K codes, then the SIR for the horizontal and vertical interference path is given by (1) and for the diagonal path it is

$$SIR(d,K) = 10\log\left[\frac{N}{K}\left(\frac{\sqrt{2}\cdot 4D + d}{d}\right)^2\right] \text{ dB} . \qquad (3)$$

The worst case SIR from (1) is 14 dB for d=D and K=N. For the diagonal path the worst case SIR of 14 dB is given by (3) with $d=\sqrt{2}$ D and K=N. The resulting total SIR is 14 dB - 10log3 = 9.2 dB. Since this SIR is the same for all subscribers in the interfered cell this prevents the whole cell from modulation formats higher than QPSK and restricts bandwidth efficiency and overall cell capacity.
To improve the interference situation, the number of codes for subscriber positions causing high interference must be limited. This can be done in a static way at setup of the network, since the upstream interference level in the second nearest cell can be derived from the topology of the network. In **Fig. 7** the SIR caused in one of the second nearest cells by a subscriber transmitting with all N codes to its base station in the lower right corner is shown. If the number of codes n assigned to a subscriber is lower than N, these SIR values are increased by 10 log(N/n). For n=N/4, the increase of SIR is 6 dB.

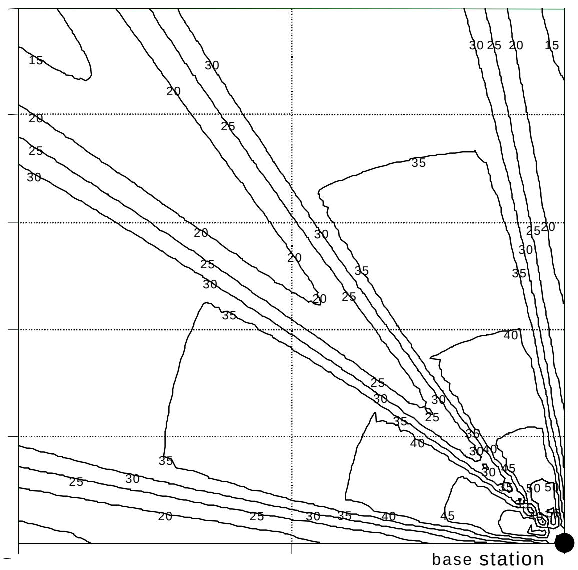


**Fig. 7: SIR in the second nearest cell caused by upstream transmission (BS at lower right corner)**

CDMA offers a possibility to increase the overall cell capacity. That is, restriction of the peak rate in the regions below 25 dB in Fig. 7 so that the worst case SIR is always higher than 25 dB. If three cells are interfering the remaining SIR is 25 dB - 10 log 3 = 20.2 dB and allows the use of 16QAM for all users in that cells, thus doubling the capacity.

## 3.2. One Frequency per Cell

### 3.2.1. Sectoring with Codes

The frequency assignment of the multimode CDMA explained in section 2.3 leads in the upstream direction to an improved interference situation. Again, we use the scheme shown in Fig. 5, assuming a bandwidth of 4W Hz, 4N codes with a spreading factor of 4N and an assignment of N codes to each sector. The worst-case SIR from each of the interfering cells is given by (2) with d = D. This value is reached only for a small angle around the sector border corresponding to the beamwidth of the antenna, and for the furthest points of the interfering cell. If, for example, the total number of codes assigned to subscribers in these areas is N/2, this gives an SIR of 18.5 dB. For K = N/4, we have an SIR of 21.5 dB. This shows that in upstream direction a given base station gets interference from only a small number of subscribers in adjacent cells. Thus, the worst-case SIR can be kept higher than with a TDMA approach with 9.2 dB according to section 3.1.

### 3.2.2. Sectoring with Antenna Beamwidth

The method described here aims at further improving the overall cell capacity without increasing upstream interference. Let us again assume a bandwidth of W Hz used in all sectors and N codes with spreading factor N. If the same N codes are assigned to each sector, we get the same cell capacity as in the previous approach with 4W Hz bandwidth and 4N codes, from which only N are assigned to a sector. However, the bandwidth is reduced by a factor of 4 in this case. Now the frequency assignment pattern as shown in Fig. 3 can be applied. This leads to a higher worst-case SIR according to the considerations in section 3.1. The separation between adjacent sectors is ensured in this case by the beamwidth of the subscriber antenna.

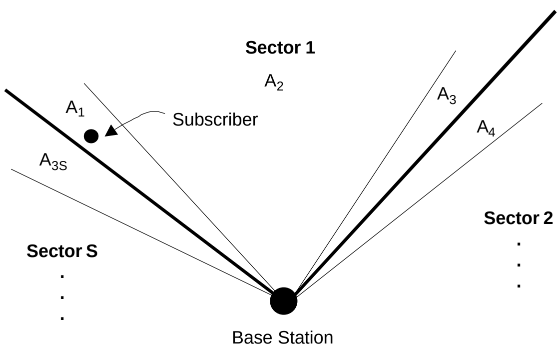


**Fig. 8: Upstream intracell interferenc areas. $A_{3S}$, $A_1$, $A_3$, $A_4$ are the overlapping areas of sector 1; $A_2$ is the non-overlapping area of sector 1.**

However, subscribers located in a small section around the sector borders can meet with their upstream beam two receiver antennas at the base station: the antenna belonging to its sector and the antenna belonging to their neighboring sector. There are again four overlapping areas and one non-overlapping area relevant for each sector (**Fig. 8**).

To avoid overlapping effects, an algorithm has to be installed at the base station which allocates downstream bandwidth observing the following conditions:

$$\mathbf{N_{3S}} \cup \mathbf{N_1} \cup \mathbf{N_2} \cup \mathbf{N_3} \cup \mathbf{N_4} \subseteq \mathbf{N}$$
$$\mathbf{N_3} \cup \mathbf{N_4} \cup \mathbf{N_5} \cup \mathbf{N_6} \cup \mathbf{N_7} \subseteq \mathbf{N}$$
$$\ldots$$
$$\mathbf{N_{3S-3}} \cup \mathbf{N_{3S-2}} \cup \mathbf{N_{3S-1}} \cup \mathbf{N_{3S}} \cup \mathbf{N_1} \subseteq \mathbf{N}.$$

If, e.g., a subscriber located in sector 1 area $A_1$ (Fig. 8) transmits with full capacity, then none of the subscribers located in the areas $A_{3S}$, $A_2$, $A_3$, $A_4$ can send any information. If all requesting subscribers are located in the non-overlapping areas, at most S*N codes can be allocated instead of S*N/2 codes when all requesting subscribers are located in the overlapping areas.

As already indicated in Fig. 8 and in the formula above, a cell can be subdivided into more than four sectors. In such cases there will no longer be the strong three-beam interference situation shown in Fig. 3 so that the intercell interference problem is defused with the increasing number of sectors.

# 4. Implementation Requirements

Besides the general architectural considerations of the systems, also some implications with respect to the practical realization should be taken into account. The methods described in this paper are based on orthogonal CDMA. Orthogonality of the spreading sequences can be affected, e.g., by chip phase synchronization inaccuracies, carrier frequency offsets, phase noise of oscillators and so on. All these effects introduce multiple access interference (MAI) to the signal and degrade performance.

To assess the influence of these basic effects, measurements with a lab test system and also some simulations were performed. The system contains a CDMA link with transmitters capable to transmit a variable number of sequences, an RF up- and down-conversion for the LMDS frequency range and a synchronous receiver.

The chip phase synchronization for the downstream is inherently given because all sequences are generated in the same transmitter or at the same base station. For the upstream each subscriber has to be synchronized with respect to the chip clock phase and the carrier frequency. This requires a closed loop phase control via the down-link and the distribution of a reference frequency to all terminal stations. The required chip clock phase accuracy turned out to be the range of 1/16th to 1/32th chip duration. Keeping in mind that the chip frequency is identical to the symbol frequency of an equivalent TDMA system (which also needs a certain time synchronization), this requirement can be fulfilled with appropriate algorithms available (e.g. [7]).

In contrast, the introduced MAI due to carrier offset is significant. A frequency offset of 0.05/N * chip frequency causes a signal-to-MAI ratio of 22 dB. For a 28 MHz channel bandwidth and a spreading factor of 128, this offset is about 10 kHz. This means that a carrier frequency offset compensation with an accuracy better than 1 ppm for an RF of 28 GHz is required for orthogonal CDMA. Although challenging, this can be accomplished e.g. by using the chip clock frequency as a stable reference frequency which is available in all network terminations and to which the carrier is locked.

Thus, the practical realization and exploitation of the orthogonal CDMA advantages seems to be in fact feasible with a certain amount of additional effort. The detailed evaluation of this topic, however, is not within the scope of this paper.

# 5. Summary and Conclusions

For the application of CDMA in LMDS networks different approaches are analyzed with respect to their worst-case interference and maximum cell capacity.

The first approach is derived from the four frequencies per cell assignment scheme commonly used in TDMA systems. In downstream direction, the intercell interference is the same for TDMA and CDMA. On the upstream, CDMA allows the restriction of the peak capacity of highly interfering subscribers. This leads to interference reduction and an increase of the overall cell capacity.

The second approach is based on the use of only one frequency per cell. It aims at increasing capacity by cell sectoring. To improve the worst-case SIR for the downlink, the multimode CDMA is presented, which allows the connection of subscribers even in the worst case areas of the sectors, however, at cost of reduced peak rate.

In the upstream, it turned out that the intercell interference with CDMA can be kept significantly lower than with TDMA. An additional increase of overall cell capacity is possible by exploiting the reuse of codes within the cell and by separating the sectors with the beamwidth of the upstream antenna. Here too dynamic control of code assignment is applied.

The specific advantages of this method are:

- The assignment is done dynamically taking into account the actual bit rate requirements, the location of the subscribers in the cell as well as the individual interference situations in the overlapping areas of adjacent sectors.
- Sector sizes can vary and therefore they can easily be adapted to topological, environmental, or structural conditions.
- To cell areas with high bandwidth demands “small” sectors are assigned having a small apex angle.
- The overall transmission capacity and the peak capacity per subscriber is improved with increasing number of sectors in a cell.

In summarizing, it can be stated that the application of CDMA to LMDS networks can offer a high degree of flexibility with respect to network planning and capacity optimization, despite some undoubted challenging implementation requirements. Although the peak rate for some subscribers located in unfavorable positions has to be reduced, the overall capacity can be increased. Limitation of the interference level is possible without synchronization of different base stations, as it would be the case with TDMA.

## 6. Acknowledgements

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