Considerations of modem design for LMDS systems

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Abstract

During the last 2-3 years, there has been a lot of activities aiming to deploy broadband wireless access systems. The US LMDS auctions in February-March 1998 of 1.3 GHz of spectrum between 27.5 GHz and 31.3 GHz triggered efforts to develop system solutions and standards that have as objective to render LMDS systems competitive to other broadband, and primarily wireline, technologies. The modem design must be matched to the channel characteristics of LMDS systems, which are very different from those of coax and even lower frequency wireless communications systems. In addition, the cost factor is a key issue to face the competition from other technologies. A modem design meeting these two constraints is described in this paper, together with an analysis of the main impairements characterizing the LMDS channel. The modem includes fully rotational invariant TCM, amplitude phase modulation (APM), equalization and linearization.

1 Introduction

In the first 5-10 years of the new millennium, we will see wave of deployment of broadband technologies, including wireline technologies like xDSL, cable modems and fiber optic cables, and satellite, stratospheric and terrestrial wireless technologies. Local multipoint distribution services (LMDS), together with other wireless technologies, has the potential to compete with wireline technologies in delivering broadband communications. However, the competition will be stiff, and the success of the LMDS technology depends on several factors. Which services that are best suited for LMDS, and which will offer operators revenue-enhancing opportunities are still not well defined. Indeed, what market that is most likely to embrace LMDS as a "last-mile" technology is still not clear. The intense competition from wireline technologies demands that these questions are given the right answers fairy quickly. If not, the potential markets for LMDS will fall into the hands of the competition.

The cost of equipment, and especially customer premises equipment (CPE), is another factor that may prove to be decisive. The major cost driver of the CPE is the RF unit, including the high power amplifier (HPA) and synthesizers. The system design should reflect this cost pattern. Efforts are under way to standardize LMDS through the IEEE 802 LAN/MAN Standards Committee, aiming to reduce component cost.

This paper contains 3 main sections. Section 2 gives an overview of LMDS network architecture and design, and discusses potential markets and services. A modem design using amplitude phase modulation (APM) and fully rotational invariant pragmatic trellis coded modulation (PTCM) is described in section 3. This coding and modulation scheme has higher spectral efficiency than the existing LMDS standards, and at the same time they relax the constraints on the RF units. The main channel impairements of LMDS systems are, in addition to the inevitable additive white Gaussian noise (AWGN), intermodulation components due to non-linear HPA, phase noise, inter-symbol interference (ISI) introduced by multipath propagation and non-ideal components, and interfering signals generated both by the system itself and by other systems. The channel is covered in section 4.

2 Overview of LMDS systems

In the US, a total of 1.3 GHz of spectrum between 27.5 GHz and 31.3 GHz was auctioned out in February and March 1998 to be used for local distribution of voice, video and data. This is known as the US LMDS spectrum. Other bands are also allocated to LMDS-type of systems at 24 GHz and 39 GHz. In Europe the band from 40.5-42.5 GHz is generally used, but there are some differences between countries. For instance, in Germany the 24 GHz band is allocated to point-to-multipoint (PMP) services, while some other countries are using the 28 GHz band. Korea and Japan use frequencies from 22 GHz to 28 GHz. DAVIC [1] defines LMDS as systems transmitting on frequencies above 10 GHz, as opposed to MMDS (Microwave Multipoint Distribution Services) systems transmitting on frequencies below 10 GHz.

2.1 System architecture

The four main elements of the LMDS network architecture are the base station equipment, RF equipment, CPE and network management system.

The base station equipment typically consists of a network interface and a modem unit. The base station is the gateway between the wireless and wireline networks, and an ATM switch typically provides the connectivity. The modem functions include multiplexing, randomization, encoding and modulation for downstream data, and the inverse operations for upstream data. It is connected to the RF equipment through the IF interface. The IF level is typically between 950 MHz and 2150 MHz.

The RF equipment is constituted by up/down conversion chains, high power amplifier (HPA), low noise amplifier (LNA) and filters. The high frequency band leads to significant line attenuation, so the RF elements are located close to the antenna. Multiple carriers on the same transceiver maximize throughput and reduce cost and complexity.

The CPE contains an out-door unit (ODU) and an in-door unit (IDU). The ODU includes a 10 to 12-inch antenna and the RF unit. The CPE IF interface connects the ODU to the IDU. The CPE modem structures the data to emulate standard interfaces like T1 or E1.

The network management system monitors the health and performance of the LMDS system by means of the agent applications and management application. It covers the operations, administration, maintenance and provisioning of the network. The agent application is management software that resides in all elements of the network. The management application is a single application operated using a graphical user interface. It allows an operator to view the entire access network, and to optimize its performance.

2.2 Network design

The high free space loss and the line-of-sight constraint characterizing LMDS networks limit the area covered by one hub. Figure 1a shows how a master cell can be connected to several slave cells, in order to cover a larger area. An somewhat different strategy is to interconnect the 3 hubs and a separate master headend by a wireless or fiber loop as shown in figure 1b. Both fully wireline systems and hybrid wireless and wired systems can be envisioned. The choice will depend on the current infrastructure, and on the available frequency resources. A system integrator with abundant spectrum may opt for a fully wireless system, where the cells are connected by wireless links, whereas an integrator with little spectrum to spare probably will go for wired links between hubs.

The size of the circular cells typically depends on the system gain of the RF equipment, the transmitting and receiving antennas, the rain region in which the LMDS system is located and the required received signal to noise ratio for acceptable system availability. Generally the cell radius will be between 2 and 8 km

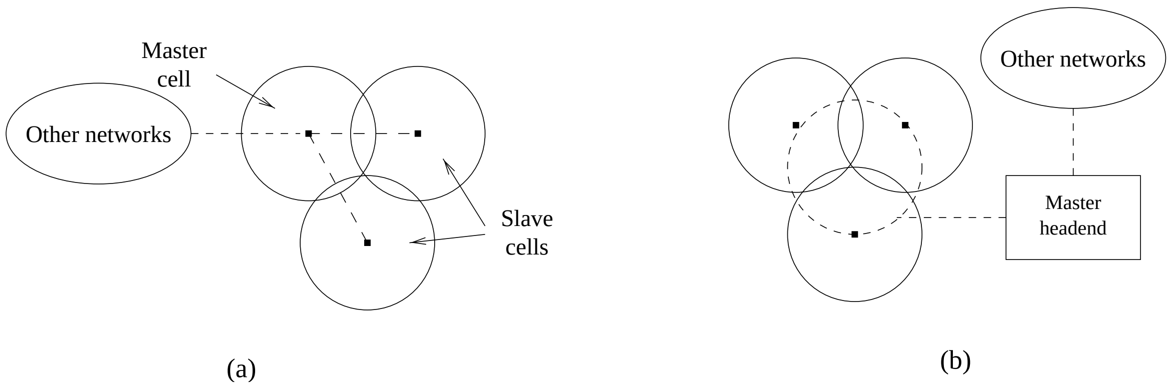


Figure 1: Cellularization of LMDS system

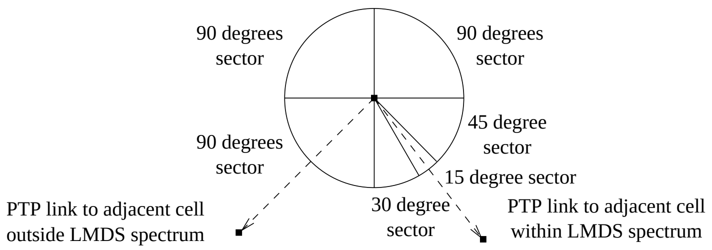


Figure 2: Sectorization of LMDS systems

with no obstructions. In practical systems obstructions like buildings, vegetation and terrain will block the signal in some directions. The shape of the cells will therefore be irregular, and even have “holes” within the cell boundaries where the signal from the hub can not be received. Careful coverage planing is necessary to maximize the availability throughout an area, and software packages using digital maps are developed to make this job easier. In some cases small active or passive repeaters within the cell can be used to reach areas not having line-of-sight to the hub. In other cases big structures can be used as reflectors. The loss due to the reflection will depend on the roughness of the surface. A third possibility is to have heavily overlapped cells. This solution also allows smart systems the ability to use alternate transmission routes in the event of degraded capability in any one cell, as a portion of the customers may receive the signal from several hubs.

Although the LMDS spectrum is large compared to frequency bands designated to point-to-point (PTP) and PMP at lower frequencies, sectorization is used to increase the capacity. In figure 2 an example of how a cell can be divided into several sectors is illustrated. An undesired effect of both cellularization and sectorization is co-channel interference (CCI). The effects of CCI on the system performance are covered in section 4.4.3.

2.3 Markets and services

Several market segments can be distinguished. LMDS operators will primarily target large businesses, and the services they will offer are trunked telephony, private data circuits, remote access and LAN interworking. These customers will be small in numbers, but will be well served by a large-bandwidth dedicated PTP link integrating a number of services. They normally have internal wired networks, with staff to maintaining it. Line-of-sight will generally not be a problem as the customer antenna typically will be placed well above the ground and surrounding obstacles.

Medium to small businesses constitute another market segment. For many of these, a dedicated private link may not be a competitive alternative to other technologies. Often they do not have staff or resources to maintain the internal network. The LMDS operator then must support parts of the internal network. If a number of such businesses are geographically concentrated, they may be well served by an LMDS system with a frequency division multiple access (FDMA) return links, and a shared forward link.

Small offices/home offices (SOHO) potentially constitute a big and ever growing customer base. LMDS operators will however be reluctant to offer LMDS to this group of several reasons. The traffic pattern is rather sporadic, calling for time division multiple access (TDMA) and a large number of users sharing the spectrum. The users are often located in leased site business parks or in single family dwellings, and it may be difficult to obtain line-of-sight between the base station antenna and the user antenna.

Residential users' demand for bandwidth increases as the PC becomes more and more ubiquitous. For multi dwelling units, LMDS systems may become an efficient alternative integrating voice, video and data services. Cable companies are however in the process of taking the lion share of this market, and it is an open question if LMDS CPEs will be able to compete in price with cable modems. Interoperable multimedia cable network systems (MCNS) compliant modems are expected to be available for \$200 to \$300 by the end of 1999 [2]. For single family homes, it is doubtful if LMDS will ever become a serious competitor to wireline technologies.

In addition to providing "last-mile" services, LMDS operators may provide PCS or cellular backhaul for other wireless carriers [3].

3 A fully rotational invariant coding and modulation scheme

Two organizations behind existing LMDS specifications are DAVIC and ETSI. The DAVIC 1.4 specifications [1] and the ETSI LMDS specifications [4] have been available since the summer of 1998. Punctured convolutional codes based on a rate 1/2 code with constraint length 7 are specified by both ETSI and DAVIC to be used in the downlink. The main advantage of these codes is the unifying implementation of the encoder/decoder with different code rates. The different code rates are achieved by adding different number of bits to the transmitted symbol sequence, requiring the modulator to operate at different data rates and hence different bandwidths. There is an other approach that has the advantage of unified implementation with different data rates, and that does not require different bandwidths. The approach is called Pragmatic trellis coded modulation (PTCM), and was proposed by Viterbi *et al.* in 1989 [5]. As for traditional TCM, the different coding rates are obtained by choosing different modulation schemes. In wireless multirate communications systems, where the number of users varies dynamically, as does their required data rates, this feature adds flexibility to the system.

3.1 Pragmatic TCM (PTCM)

The optimum TCM codes for additive white Gaussian noise (AWGN) channels are the so-called Ungerboeck codes [6]. The PTCM codes constitute a suboptimum solution allowing to implement several coding rates using the same encoder. Decoders with identical trellis connectivities make it very easy to implement a common decoder for all the data rates. The PTCM encoder is illustrated in figure 3 for 4-, 8-, and 16-PSK modulation. The convolutional code is of rate 1/2 with constraint length 7, and is the same that is used by the ETSI and DAVIC LMDS specifications. This code has been around since the early 1970s [7], and a VLSI implementation has been available for over 10 years [8]. For QPSK, the PTCM encoder works identically to the convolutional encoder with rate 1/2. The two outputs of the encoder define one out of 4 symbols in

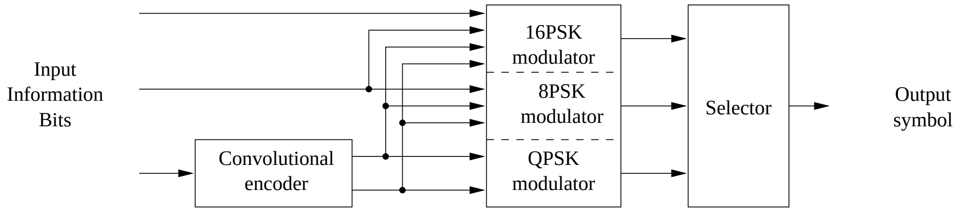


Figure 3: Pragmatic TCM encoder for MPSK signals

the constellation using Gray mapping. For 8PSK, these symbols are uniformly located in either the right or left half-plane, with the remaining uncoded bit defining which half-plane to choose. For 16PSK, the four symbols are located in one of the four quadrants. The two uncoded bits are used to choose the quadrant. This principle can be generalized to arbitrary MPSK with $M = 2^{m+1}$. In each case the lowest-ordered of the m input bit is fed to the encoder whose output bits define one of four phases within a sector $(2\pi/2^{m-1})$ rad using Gray mapping. The remaining $m-1$ bits select the sector lexicographically [5]. The performances of PTCM codes are very close the performance of the Ungerboeck codes. With 16PSK modulation, the performances are close to identical for all BERs of interest. With 8PSK modulation, the performances are close to identical for BERs down to 10^{-4}. For lower BERs the coding gain of the PTCM is a lower than that of the Ungerboeck code. At a BER of 10^{-5} the difference is still small, about 0.3 dB [5].

To obtain quasi error free (QEF) transmission, i.e., a bit error rate about $10^{-10}-10^{-11}$, PTCM is used in combination with convolutional interleaving and outer Reed-Solomon coding. The size of the interleaver must be matched to the characteristics of the channel and to the coding and modulation scheme. The size of the RS code must be adapted to packet lengths.

3.2 Amplitude Phase Modulation (APM)

The modulation schemes specified by ETSI [4] and DAVIC [1] are QPSK and DQPSK. The exception is DAVIC's optional 16QAM without inner coding for the downlink. Due to its low spectral efficiency of only 2 b/s/Hz, QPSK is becoming less attractive. However, there are several reasons why the spectral efficiency should not be chosen too high either. One obvious reason is the extra power needed to achieve the same performance as systems with lower spectral efficiency. The cost of the high power amplifier (HPA) increases with the transmitted power. The HPA also introduces nonlinear distortion that may do severe damage for

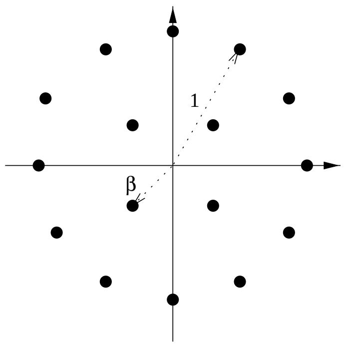


Figure 4: The 16APM constellation diagram

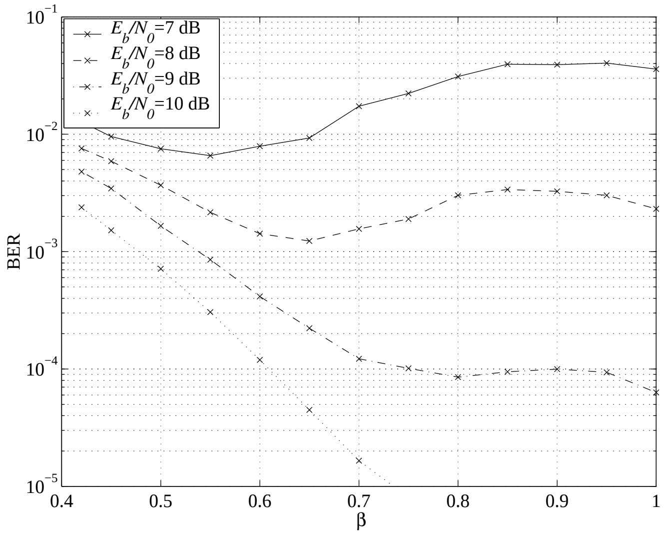


Figure 5: Simulated BER as a function of the ring ratio β and E_b/N_0 for 16APM.

multi amplitude constellations with large envelope fluctuations. The system also becomes more sensible to other channel impairements like CCI. The result is that the requirements on the system architecture become very strict, and hence, the cost of the equipment very high.

PTCM can be used with other modulation schemes than MPSK. In this paper a modulation techniques with 4 bits per symbol is considered. 16APM (amplitude phase modulation) [9] has 4 constellation points on an inner circle, and 12 constellation points on an outer circle (see figure 4). The optimum ring ratio β for transmission over an AWGN channel maximizes the minimum Euclidean distance between the points in the constellation, and is approximately 0.42. For PTCM coding, different bits have different error protection as only one out of $M-1$ is coded. The optimum β value is therefore different than that for uncoded transmission. In figure 5, simulation results for the bit-error-rate is shown for different signal to noise ratios and β's. The positions of the points on the outer circle are modified so that the minimum distance between points on different rings are equal to the minimum distance between the points on the outer circle. Hence, with a ring factor of 1, the constellation corresponds to 16PSK. For low E_b/N_0 values, optimum β is close to 0.42, while for high E_b/N_0 values the optimum β value increases towards 1. Which ring ratio to choose then depends on the working point of the decoder. When Reed-Solomon outer coding is applied, for instance RS(204,188), a bit error rate at the output of the PTCM decoder of $7 \cdot 10^{-4}$ gives a BER at the output of the RS decoder of about $10^{-10} - 10^{-11}$. In this area a ring factor of about 0.75 seems to be close to optimal.

When different signal constellations are compared, the average energy per symbol is often normalized to 1. When the maximum signal level is limited by the HPA, it is more interesting to compare the performance with normalized maximum symbol energy. In figure 6, the simulated BER for PTCM with different 16-ary modulation schemes are depicted with normalized maximum signal level. 16APM and 16PSK give quite similar performance. The principal reason to choose 16APM is to obtain fully rotational invariance. The performance with RS outer coding is illustrated in figure 7. Ideal interleaving is assumed. The BER at the output of the RS decoder is calculated as a function of the input BER using equations from [10].

3.3 Rotational invariance

Most practical signal constellations have rotational symmetries. The rotation of the 16APM constellation about the origin by $i \cdot 90°$ leaves the constellation unchanged for all integer i. For 16PSK the same is the

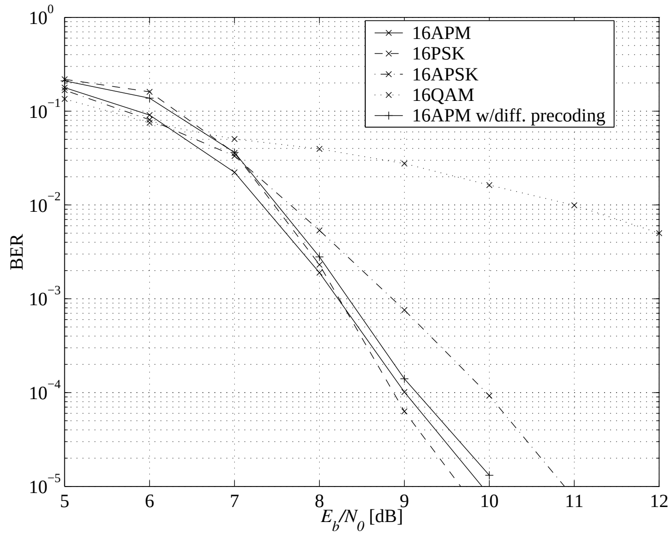


Figure 6: Simulated BER with PTCM encoding and different modulations.

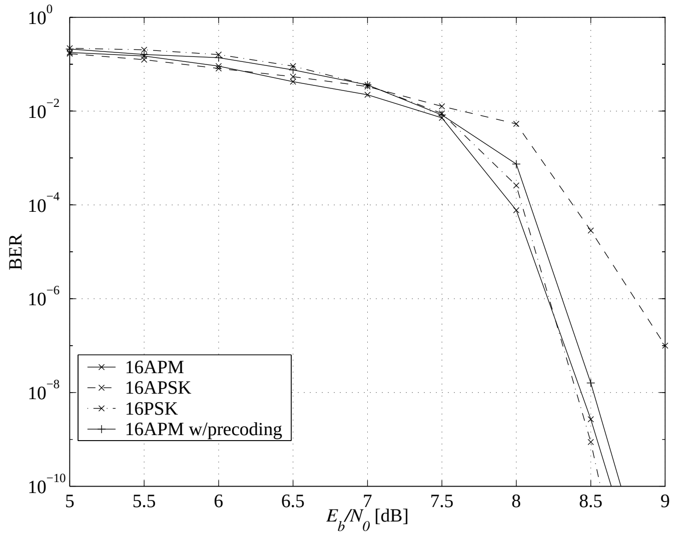


Figure 7: Simulated BER with RS(204,188) outer coding and PTCM inner coding coding and different modulation schemes. For 16APM the ring vector β is set to 0.75, and for 16APSK it is set to ($\beta = 0.7$).

case for rotations by $i \cdot 22.5°$. The rotational symmetries introduce phase ambiguities in the receiver. If the receiver locks to a wrong carrier phase, and if the rotated sequence does not belong to the code, a long sequence of decoding errors will occur. Rotational invariant TCM (RI-TCM) schemes avoid this problem by ensuring that a rotated code sequence is always another code sequence and that all rotations of a code sequence decode to the same information sequence. Thus, the receiver ignores the phase ambiguities rather than to try to resolve it.

For PTCM coding, rotational invariance can be obtained by the use of differential precoding. Phase ambiguities of multiples of $2\pi/2^f$, where f is the number of inputs to the differential precoder, are resolved using this form of differential encoding. Hence, to obtain $\pi/2$ rotational invariance, it is enough to differential encode two of the three encoder inputs, as illustrated in figure 8. Denoting the input and output of the

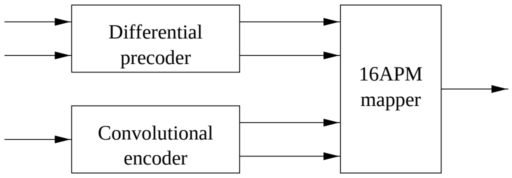


Figure 8: PTCM encoder with differential precoding

differential precoder at instant $t = kT$ a_k and b_k, respectively, b_k is given by:

$$b_k = (a_k + b_{k-1}) \bmod 2^f$$

where $a_k, b_k \in \{0, \ldots, 2^f - 1\}$. In figures 6 and 7, the simulated BER with differential precoding is included. The loss due to the differential precoding is about 0.15 dB.

4 The LMDS channel

The LMDS propagation channel is studied though technical trials and propagation measurements several places around the world. The attenuation of the signal depends on factors like distance (free space loss), rain, clear air absorption and obstructions by vegetation, solid structures and terrain. In addition, the non-linear HPA, phase noise, multipath and interference are important impairements to be taken into account.

4.1 Attenuation through propagation

The free space loss is well known, and can be expressed as a function of frequency and distance as $L_s = 92.45 + 20\log(fd)$, where L_s is given in dB, f is the frequency in gigahertz and d the distance in kilometers.

Attenuation from precipitation will in many cases be the most significant threat to availability and QoS. It is necessary to include rain margins in the link budget in order to obtain required system availability. The attenuation depends on drop size, drop shape, rain rate and rain cross section. These factors depend on the climate, and rain region maps have been proposed by the ITU-R. The maps indicate the level of rain attenuation to be included in the link budget for a certain region and system availability. Examples for Dallas and Chicago show 3.95 dB/km and 2.28 dB/km loss for a system availability of 99.9 %, respectively [11].

Another effect of precipitation is losses due to water, snow or ice being in or on the outside of the antennas. Even a thin layer of a mixture of water, snow and ice on a horn feed leads to a loss of several dB [13].

Molecular oxygen and water vapor lead to additional attenuation, which varies slowly with temperature, pressure and humidity. In most areas the loss per km is less than 1 dB.

Vegetation may lead to serious signal degradation if it obstructs the line-of-sight. For typical LMDS links, the antennas will by located well above the ground, and obstructing vegetation will be trees. Measurements with coniferous and deciduous trees indicate that the loss is in the order of 1-2 dB/m for the first meters of foliage [12].

Solid structures and terrain obstructing the line-of-sight will generally make reception impossible. Diffraction at this frequency band is practically non-existent, as the "shadow" becomes very sharp. Reflections of

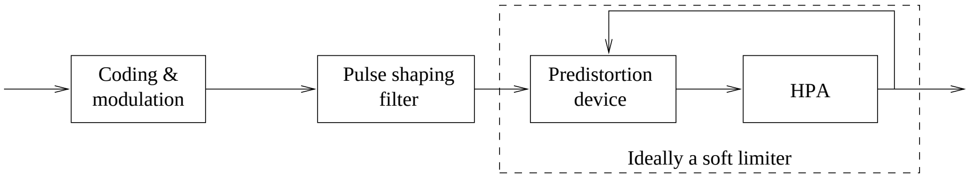


Figure 9: System model or evaluation effects of the non-linear HPA

surfaces may create problems in form of discrete multipath. By careful placement of the antennas discrete multipath will in most cases be avoided.

4.2 Distortion due to the HPA

Different HPAs are needed for the hub and for the CPE. While the hub typically transmits over 1 W, the transmitting power of the CPE typically is much lower ($\sim$ 0.1 W). The HPA generates intermodulation products (IMP) due to nonlinearity. The nonlinearity has two effects on the transmission system. The first is spectral widening of the signal, which leads to out-of-band interference or adjacent channel interference (ACI) in a multichannel signal. The second effect is distorted signal components within the channel bandwidth. As the output of the pulse shaping filter is distorted, the matched filter in the receiver is no longer matched to the transmitted signal, and intersymbol interference (ISI) is introduced. Driving the HPA close to saturation impairs the nonlinear effects. A simple approach to avoid nonlinear distortion is to back-off the amplifier several decibels from the saturation region, keeping the signal level in the linear amplification range. Unfortunately, this results in lower output power, and less efficient operation of the HPA. Hence, there is a tradeoff between the power efficiency and linearity in the design of the system.

Figure 9 shows the system model used for evaluating the effects of the HPA. It contains a pulse shaping filter, a predistortion device and a HPA. In the next three subsections these three parts are described.

4.2.1 Pulse shaping filter

In order to see the effect of the HPA on the system performance, it is necessary to know the characteristics of the input signal. The pulse shaping filter is a square root Nyquist filter, where the full Nyquist filter has a cosine roll-off factor denoted α. In modern communications with limited frequency resources, the roll-off factor is low, typically between 0.15 and 0.35, reducing the excess bandwidth. A low α has the disadvantage of relatively large overshoots when the signal goes from one level to another. To reduce this effect the pulse shaping filter can by multiplied by a windowing function. Typically, a Hamming or Hanning window function is used.

4.2.2 The traveling wave tube (TWT) amplifier

In order to simulate the nonlinear effects, a commonly used model of the traveling wave tube (TWT) amplifier is applied. The input to the amplifier can be expressed by:

$$x(t) = A(t)\cos(\omega_0 t + \theta(t))$$

Non-linear distortions can be instantaneous or with memory. It is generally assumed that it is instantaneous, a hypothesis that holds when all the circuit time constants are much smaller than the signal envelope

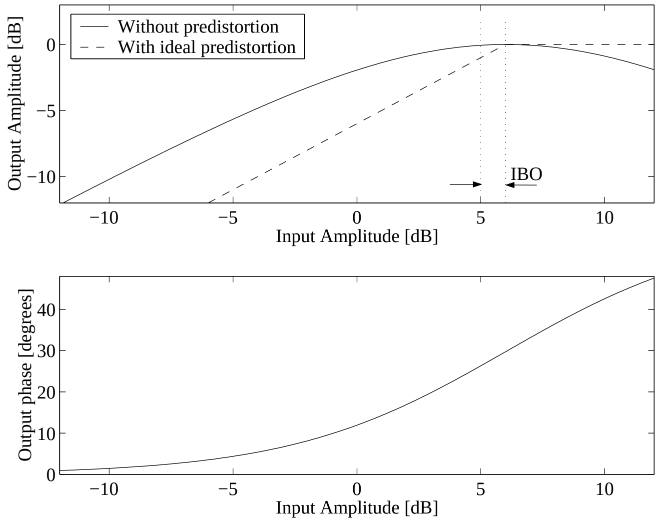
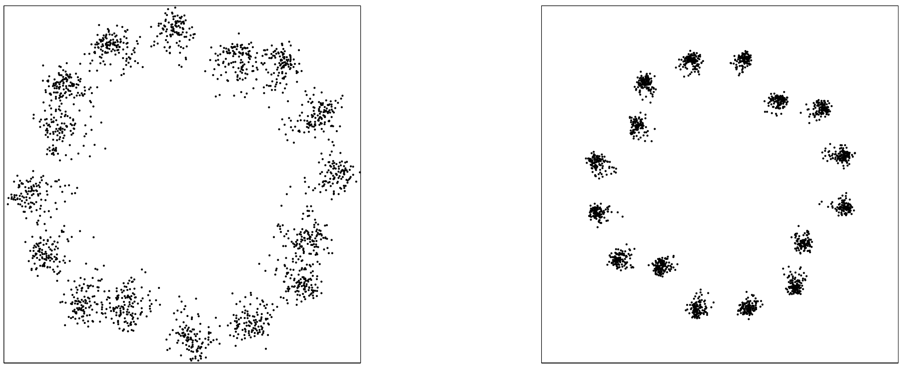


Figure 10: AM/AM and AM/PM characteristics for the HPA.



(a) (b)

Figure 11: Scatter diagram with 16APM modulation ($\beta = 0.75$) with the TWT without predistortion. a) IBO = 1 dB, b) IBO = 6 dB.

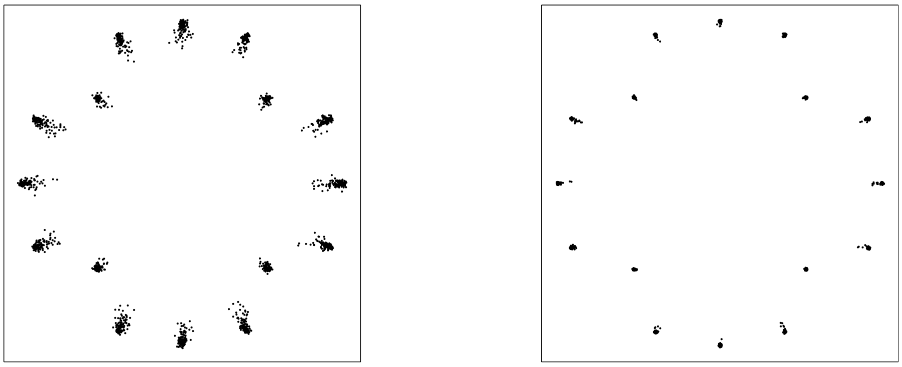
frequency [14]. In bandlimited transmission this will generally be the case [15]. The output is distorted both in amplitude and phase:

$$y(t) = G[A(t)] \cos(\omega_0 t + \theta(t) + \Theta[A(t)])$$

where G and Θ represent the amplitude and phase nonlinearities, respectively, and are typically modeled as follows:

$$G[A] = \frac{\alpha_1 A}{1 + \beta_1 A^2}\ , \qquad \Theta[A] = \frac{\alpha_2 A^2}{1 + \beta_2 A^2}$$

The parameters α_1, α_2, β_1 and β_2 are generally found by least-square fitting of the amplitude and phase characteristics of the TWT. In [16] the following values have been used: $\alpha_1 = 1.0$, $\beta_1 = 0.25$, $\alpha_2 = 0.26$ and $\beta_2 = 0.25$. In figure 10 the AM/AM and AM/PM curves are illustrated with these parameters. The scatter diagram of the output of the TWT is shown in figure 11. As expected, the received signal degrades, even with a large input back-off (IBO). With IBO equal to 6 dB, the degradation can be expected to be large enough to cause severe BER degradation.



(a) (b)

Figure 12: Scatter diagram with 16APM modulation ($\beta = 0.75$) and perfect linearization. $\alpha = 0.2$. a) IBO = 1 dB, b) IBO = 3 dB.

4.2.3 Linearization and predistortion

There are several approaches to compensate for the nonlinearity, including feed-forward linearization [17], Cartesian negative feedback linearization [18] and predistortion. The most widely used technique is predistortion [19]. The predistortion may be done digitally in baseband [20], or by analog processing [21]. The predistortion device should in any case be adaptive in order to compensate for the varying HPA characteristics due to temperature variations, aging, etc..

With ideal predistortion, the cascade of the predistorting device and the HPA has no phase distortion, and the amplitude distortion may be modeled as a soft limiter as illustrated in figure 10. Hence, clipping can not be avoided when input exceeds the saturation point. Some input back-off (IBO) from the saturation point is therefore necessary to avoid distortion.

The scatter diagram of the output of the HPA with ideal predistortion is illustrated in figure 12 with a IBO of 1 dB there is some degradation of the signal while with an IBO of 3 dB, the degradation is very small. The corresponding BER curves are shown in figure 13. With a IBO of 3 dB, the degradation is very small. With an IBO of 1 dB however, the loss is about 0.6 dB.

4.3 Phase noise and carrier phase synchronization

The high frequency band makes phase noise a problem for LMDS systems. The main source of the phase noise is the millimeter wave local oscillator [11].

The receiver will loose the phase synchronization due to phase snaps, phase clicks or cycle slips. With non-rotationally invariant coding, the loss of sync results in a long burst of errors. With fully rotationally invariant PTCM coding, a phase snap will result in a short error burst at the output of the PTCM decoder. When the synchronization is reestablished, the decoder will right a way function correctly. The deinterleaver will spread the error burst out, and the outer RS decoder will digest the error bytes. Hence, the phase snap may have no impact on the BER. The increased insensitivity to loss of phase synchronization relaxes the constraints on the LNA and the VCO, permitting the use of lower cost components [22].

4.4 Effect of interference

An important channel impairment is interference from other communications systems (inter-system interference), and interference generated by the system itself (intra-system interference). For US LMDS systems,

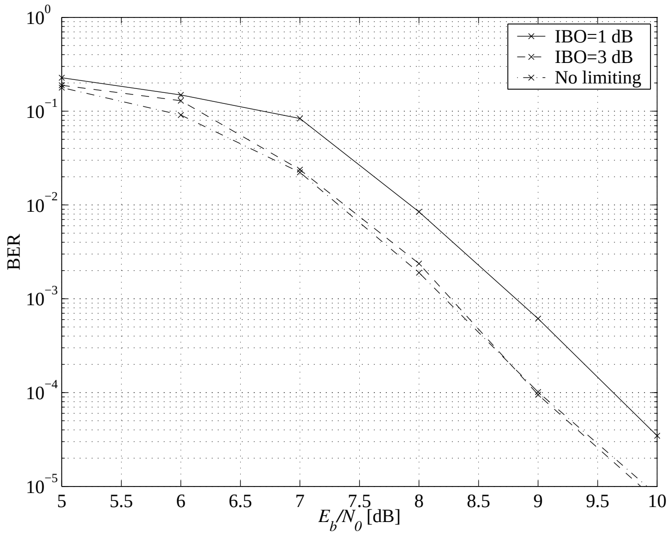


Figure 13: BER as a function of E_b/N_0 with 16APM modulation ($\beta = 0.75$), PTCM coding and ideal predistortion (soft limiting).

sources of inter-system interference include Ka-band satellite systems, stratospheric communications systems and other terrestrial (LMDS) systems. The intra-system interference include adjacent channel interference (ACI), intersymbol interference (ISI), and co-channel interference (CCI) due to frequency reuse. There are basically three approaches to reuse the frequency band, and they can and in many cases will be combined. That is sectorization, cellularization and polarization. This section deals with the impact of interference on the system performances.

4.4.1 ACI

As seen in the previous section, the non-linear HPA introduce spectral widening that may put some of the transmitted energy in adjacent channels, causing ACI. The transmitter power spectral mask defines maximum interference with adjacent channels. By adjusting the guard band between the channels, the ACI can be made so small that it has no impact on the system performance.

4.4.2 ISI

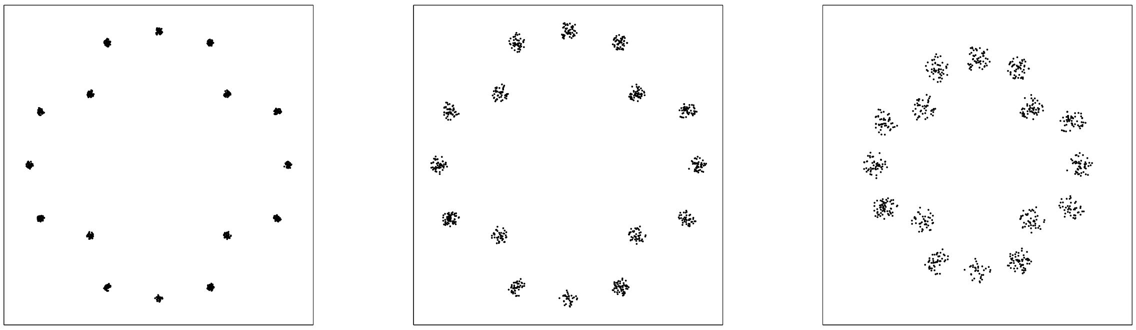
ISI is caused by multipath interference and non-ideal components. In table 1, results of a measurement campaign published in [23] are given. The transmitter and receiver antennas were mounted on 28-ft masts, and the propagation channels were partly obstructed by 30 to 50-ft tall trees. Three different channels are defined, a good, moderate and a bad channel. For all three channels, the delay spread is short. Compared to a symbol duration of 20 ns, corresponding to a channel bandwidth of 50 MHz, it is less than one tenth. It will consequently not lead to noticeable ISI. Table 1 indicates however that the delay spread increases with the distance. For distances of several kilometers the delay spread may become so long that it has an impact on the system performance, and equalization is necessary. In order to adapt to different channel conditions, the equalizer must be adaptive.

Measurements in Europe show even shorter delay spread. In [13], measurements in Oxford, UK, gave a delay spread in the order of 0.01 ns over a 2.5 km link with clear LOS.

In figure 14, examples of how the ISI may affect the signal is illustrated using the tap delay model $h(t) = \sum_{n=1}^{N} \beta_n \delta(t - \tau_n) exp(j\, \omega_c \tau_n)$. β_n is the tap gain, τ_n is the tap delay and ω_c is the carrier frequency.

Quality	d [m]	A [dB]	S [ns]	L_b [dB]
Good	122	6.2	1.26	111.7
Moderate	309	32.2	1.60	145.9
Bad	419	32.6	2.95	159.4

Table 1: Results from measurements done in Northglenn, Colorado [23] (d: distance, A: attenuation, S: delay spread (20 dB threshold), L_b: transmission loss)



(a) (b) (c)

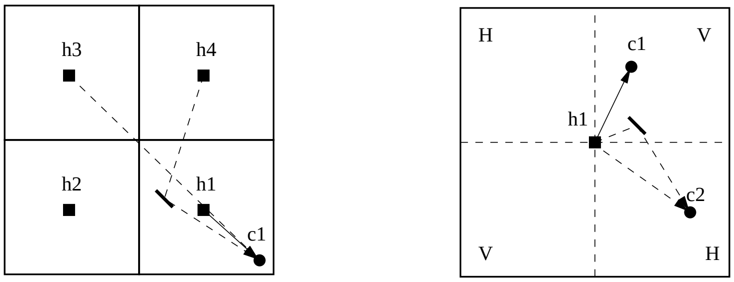
Figure 14: Scatter diagram with 16APM modulation ($\beta = 0.75$) with ISI. a) $N = 2$, $\tau_n/T = (0, 0.1)$, $\beta_n = (1, 0.2)$, b) $N = 3$, $\tau_n/T = (0, 0.1, 0.2)$, $\beta_n = (1, 0.4, 0.1)$, c) $N = 4$, $\tau_n/T = (0, 0.1, 0.2, 0.3)$, $\beta_n = (1, 0.5, 0.3, 0.1)$

4.4.3 CCI

In section 2.2 it is explained how cellularization and sectorization are used to increase system capacity and availability. If each cell is assigned its own frequency band, the LMDS spectrum will be fragmented, and the data rate offered to customers reduced. It is consequently desirable to reuse the same frequency band in several cells. The price to pay for this increase in capacity is inter-cell interference. In figure 15a, a schematic example of inter-cell interference is illustrated. There are four cells, for convenience drawn as squares, each with a hub in the center, and one customer. The customer is located close to the extension of the line between h3 and h1. The signal from h3 will then interfere with the signal of interest from h1, if there is no obstruction in between. Signals from other hubs may also interfere if they are reflected by for instance tall buildings.

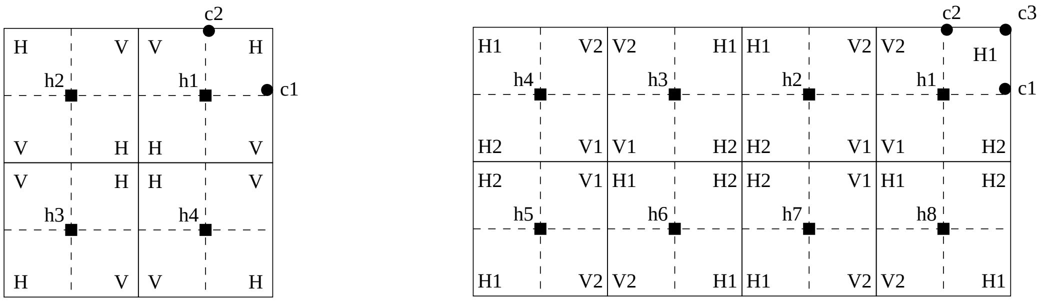
To further increase the capacity of the system, each cell can be divided into sectors. In figure 15b, a cell with four 90° sectors is illustrated. The hub antenna has a beam width of 90°, and signals transmitted to c1 would ideally not reach c2. Practical antennas have a first sidelobe level of about 22-25 dB down from the main lobe, and some energy will leak out in the direction of c2. Reflections may also lead to interference. Sectorization is generally used in combination with polarization diversity, where adjacent sectors are assigned opposite polarization. This is illustrated in figure 15b, where H and V denote horizontal and vertical polarization, respectively. The polarization discrimination is about 18-20 dB [22].

Both inter- and intra-cell interference can be reduced through a range of approaches. Spatial isolation reduces the inter-cell isolation, but will also reduce the system availability. A combination of frequency planning and polarization reduces both inter- and intra-cell interference. The customer antenna typically has very narrow beamwidth, about 2°- 3°. The major part of the inter-cell interference entering the receiver will therefore come from close to the same direction as the signal-of-interest. Assuming no obstructions, the interfering signal is then discriminated only by free space attenuation. In figure 16a, a polarization plan



(a) (b)

Figure 15: Example of (a) inter-cell and (b) intra-cell CCI



(a) (b)

Figure 16: Frequency and polarization plan with (a) 1 frequency, 2 polarizations and 90° sectors, and (b) 2 frequencies, 2 polarizations and 90° sectors.

is illustrated with the same frequency band used by all cells. Each cell is divided into four 90° sectors. Neighboring sectors have opposite polarization. The locations c1, c2 and c3 are the worst position within the sector when it comes to C/I. For c1, the signal of interest is transmitted by h1, and has horizontal polarization. The strongest interfering signals are transmitted from h1 with vertical polarization, and from h2 with horizontal and vertical polarization. With a polarization isolation of 18 dB, these three main sources of CCI give a C/I of 18 dB, 9.54 dB and 27.54 dB, respectively. The total C/I becomes 8.9 dB.

In figure 16b, the frequency and polarization plan with two frequency bands, two polarizations and 90° sectors is illustrated. Hn and Vn, $n = 1, 2$, denote horizontal and vertical polarization using frequency band n. The customers at locations c1, c2 and c3 now experience the worst C/I. At c1, the signal of interest is transmitted from h1, uses frequency band 1 and has horizontal polarization. The main sources of CCI are the signals transmitted by h2 with vertical polarization, and from h3 with horizontal polarization. The C/I for the two CCI sources are equal to 13.97 dB and 27.54 dB, respectively. The total C/I becomes 13.8 dB. With the use of 2 frequency bands instead of one, the worst case C/I is then improved by 4.9 dB.

The scatter diagram of the input signal of the decoder with CCI is illustrated in figure 17. The signal is severely degraded, even with relatively high C/I level, and a C/I equal to 8.9 dB will in most cases make communications impossible. The impact of the CCI on the BER performances is illustrated in figure 18. Even with a C/I of 18 dB, the loss with respect to CCI-free transmission is about 1.5 dB. For C/I equal to 13.8 dB, the loss is about 4-5 dB and the BER reach an error floor between 10^{-3} and 10^{-4}. With a C/I of 8.9 dB, the error floor is above 10^{-1}.

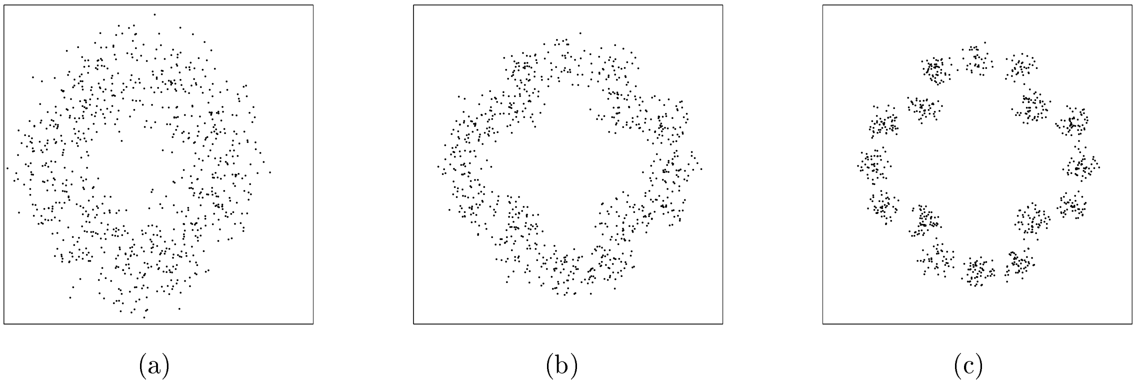


Figure 17: Scatter diagram with 16APM modulation ($\beta = 0.75$) with CCI. a) $C/I = 8.9$ dB, b) $C/I = 13.8$ dB, c) $C/I = 18$ dB.

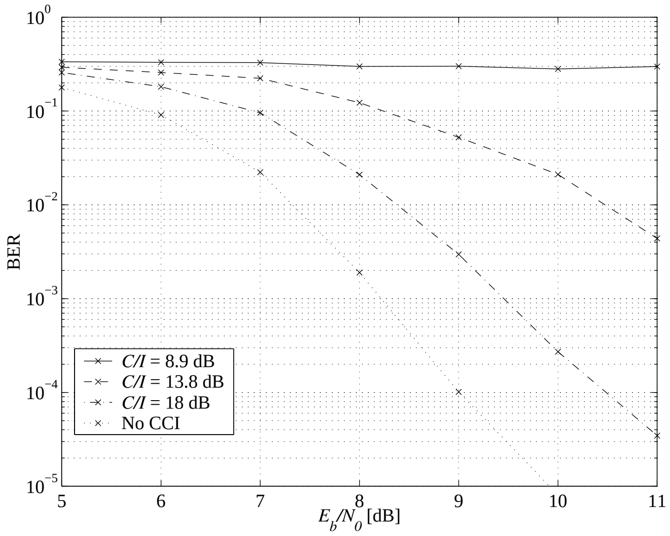


Figure 18: BER for PTCM with 16APM modulation ($\beta = 0.75$) with CCI.

The average C/I level across the cell will be much higher than the worst case figures, the directive antennas, obstructions and more favorably locations will make sure of that. To be able to guarantee system availability of for instance 99.9% or 99.99% to all subscribers, the worst case figures must nevertheless be taken into account.

4.4.4 Inter-system Interference

In the US, LMDS systems share the 28-31 GHz band with satellite communications systems. The FCC has designated portion of this band to geostationary orbit (GSO) fixed satellite services (FSS), non-geostationary orbit (NGSO) FSS, and to feeder links for NGSO mobile satellite services (MSS). Of the three NGSO MSS systems Iridium, Globalstar and ICO, Iridium is the only one to have chosen Ka-band frequencies. It uses the frequency band 29.1-29.3 GHz for uplink communications between gateways to satellites. Teledesic is a NGSO FSS system that will be using the band 28.6-29.1 GHz for uplink communications when it starts operation sometime between the year 2003 and 2005. GSO FSS systems like Astrolink and Spaceway, starting operation in 2001 or later, will use the band 29.25-30 GHz for uplink communications. Of all these systems, Teledesic is probably the one that might cause trouble for LMDS operators. The Iridium gateways are fixed, and with some system and cell planing it should be possible for LMDS operators to avoid interference from them. The GSO satellites are fixed with respect to the earth surface, so the same is the case for them. If Teledesic, with its large number of NGSO satellites, gets a lot of subscribers in an area covered by an LMDS system, there might be interference problems. However, Teledesic will primarily provide backbone communications and not "last mile" services, so the number of user terminals within the vicinity of the coverage area of a LMDS system should be small. The level of interference will depend on factors like out-of-band transmission level for Teledesic terminals, and minimum elevation of satellites communicating with ground terminals.

Two conceptually different system solutions exist for stratospheric communications systems. They are manned or unmanned aircraft circling over the coverage area, and aerostats or balloons. The main exponents for the two solutions are the HALO system from Angel Technologies, and SkyStation, respectively. SkyStation will not constitute a source of interference for LMDS systems as it uses the 47-48 GHz band. The HALO system, on the other hand, sees the use of the LMDS frequency band as one out of several options. That could potentially create a problem due to the high altitude of the aircraft. It is however likely that if HALO is allowed to lease LMDS frequencies from an LMDS licensee, it will be under the conditions that its signals do not interfere with nearby LMDS networks.

If the LMDS band in an area is shared between several operators in the same area, that might be source of interference. A portion of block A is squeezed between the two portions block B. As block A and block B licenses were auctioned out separately, two different LMDS operators may serve the same area.

5 Conclusions

The next 5 years will be crucial for the success of LMDS, at least in North-America and Western Europe. If LMDS operators have not by then obtained a fair share of the market, it will probably be safely in the hands of wireline technologies like xDSL, coax and fiber.

Standards and specifications already developed for LMDS reflect the kind of out-dated view that LMDS is a competitor to cable TV, primarily providing analog and digital television to residents. Even though the standards open for interactivity, they are not well adapted to the new world of integrated multimedia. New standards need to be developed to render LMDS systems competitive, and this work is under way through the IEEE 802 LAN/MAN Standards Committee.

LMDS systems tend to be interference limited due to frequency reuse. The interference level makes higher order modulation schemes like 64QAM impractical. Careful cell planing and antenna placement is necessary to reduce the interference to a minimum and at the same time maximizing the availability throughout the coverage area.

A key issue in modem design is to reduce the cost of the RF units, which represents the main cost drivers. The modem must be designed with this in mind, and it must be matched to the LMDS channel. The modem design described in this paper contain fully rotational invariant PTCM coding that makes the receiver less sensitive to phase snaps, predistortion that reduces the effects of non-linear HPA and adaptive equalization that reduces the impact of ISI due to multipath propagation and non-ideal components. An interleaver spreads out the error bursts at the output of the PTCM decoder, and Reed-Solomon outer coding reduces the BER down to QEF transmission.

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