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Two-layer LMDS system architecture: DAVIC-based approach and analysis

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Summary

Despite the growing interest for LMDS systems there have been only a few commercial implementations until now especially outside of the U.S.A. The use of hierarchial structure through two-layer networking has been even rarer. In many cases LMDS systems have strong advantages against its competitors to cover the last mile. In this article, we review and analyze the standards currently available and describe the European two-layer trial system developed in 1996–2000. We show why further development towards IP based LMDS is useful in the future. Most of our recommendations are based on results derived from the European Union supported research project CABSINET. It had the aim of demonstrating the viability of a 40 GHz cellular digital television system with a return channel to offer interactive services. Two systems were tested: a line of sight link using QPSK, and a non-line of sight with COFDM modulation scheme. In the RF-subsystems, the greatest difficulty of any viable LMDS system is to obtain a moderately low price for the user receiver, while fulfilling the hard OFDM requirements in terms of phase noise, stability and spectrum restrictions. Several options have been studied in order to design the subsystems with the smallest cost. This paper will present the architectures of the transmitters, nomadic terminals, and the design of the IF/RF subsystems for both types of modulations. The discussion is focused on system engineering and selections required in order to build a full two-layer LMDS system. Copyright © 2002 John Wiley & Sons, Ltd.

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1. Introduction

Cost-effective, fast and interactive broadband services will be demanded increasingly in the future. One of the key issues will be the implementation of access networks able to connect every potential user to the core broadband network. Local Multipoint Distribution Service (LMDS) is a microwave broadband system based on wireless transmission. This technology resembles cellular telephony in its manner to service groups of users by distributed base stations (BS). However, there are several differences between LMDS and cellular telephony networks. First of all LMDS is using microwave frequencies, typically at 28, 38 or 40 GHz depending on local regulations. This is obviously not the cheapest or the easiest frequency range to work with, but it has the benefit of offering up to 2 GHz of bandwidth. This is naturally a strong business advantage when competing with other wireless access methods, because no other wireless network can offer such a large capacity. Besides, cell size range can be chosen to be from a few hundred meters up to 5 km. Hence, it is possible to guarantee the scalability of the system depending on local population density. In Europe several frequency bands from 24 GHz to 43.5 GHz will be available for point-to-multipoint applications. One should note that these bands might be referenced not only to LMDS, but also to related systems which are called Fixed Wireless Access (FWA).

The origin of LMDS resides with traditional Multichannel Multipoint Distribution Systems (MMDS) that work mostly at frequencies lower than 5 GHz with large coverage areas (cell radius can be up to 50 km). They are suitable for transmission of video and broadcast services in rural areas, but because of the large cell dimension, they are not very well designed to integrate a return channel for interactive services. LMDS systems are working at higher frequencies, where larger portions of frequency are available. The coverage is realized with smaller cells (typically below 3 km) and systems usually require repeaters to be placed in a Line of Sight (LOS) configuration. This local coverage together with the large available bandwidth can make these systems suitable for interactive services. We will be arguing that although LMDS was originally seen as ‘wireless cable’ and just a high-frequency version of MMDS, it is well suited to work as Wireless Local Loop (WLL) for data and voice services too.

Fixed Low-Frequency FWA (which are also wrongly referred as LMDS) systems typically operate at 3.5 GHz and 10.5 GHz frequencies [1]. A number of standardization groups have addressed both low-frequency and high-frequency FWA issues including ITU, IEEE, ETSI and national regulation bodies. In this paper we do not focus on low-frequency FWAs but refer the reader to Reference [1]. However, we want to stress that these low-frequency systems can work as a part of a hierarchial two-layer LMDS network very effectively as will be discussed in this paper.

Although LMDS frequencies have been initially allocated for broadcast networking applications in several countries [2, 3], it can be used for two-way transmissions, providing support for interactive services. Hence, LMDS is an economically competitive alternative for last mile connectivity. It is also often a viable alternative, e.g. for fixed lines. The main part of the costs during the deployment phase are from base stations. New costs are incurred only as additional customers sign on. The large and static investment related to burying cables do not exist with LMDS.

Finally the broadband speed promised by LMDS is more than tempting. Such systems can deliver dozens of down link channels each transmitting 10 to 50 Mbit s^{-1} data streams in a typical configuration, while the uplink might provide from 64 Kbit s^{-1} to a few Mbit s^{-1} per user [3–5].

LMDS systems are starting to emerge same time as a technological revolution has begun in television broadcasting. The importance and repercussion of digital television are comparable to the introduction of color transmissions. The development towards all digital television broadcasting seems to be unstoppable as a consequence of the volume of business. It offers users the following novelties:

- Dynamic television services, e.g. ‘Pay per view’.
- Very large number of channels.
- Possibility for broadband multimedia interactive services.
- Broadband Wireless Internet connection not only through television, but through a set-top-box also for other devices such as a PC.
- Possible integration of all the domestic audiovisual terminals, through home networking and set-top box.

The interactive and digital television operations are, of course, natural applications for LMDS. Using most of the frequency for downlink broadcasting enables potentially hundreds of digital television channels over 2 GHz of bandwidth. However, we argue strongly that this would not use the full potential of LMDS. It is fundamentally a last-mile access technology, and should not be limited for wireless video and television broadcasting. On the contrary, LMDS should be used as a generic fixed wireless digital transmission system. The extra services that can be provided are:

- Internet connectivity; wireless IP to home. The base stations can provide access to IP and ATM networks.
- Fixed Wireless Local Loop for telephony services. This can include both ISDN/POTS telephony but also Voice-over-IP.
- Audiovisual services like with MVDS.

In fact, most potential users have a Small Offices and Homes (SOHO) environment. LMDS is a very tempting model for independent operators who want to build a market presence in the areas where an established operator governs over the most of the copper line infrastructure. This is the case in several European countries. It also enables the possibility to bring in services quickly into the areas where the user demand is increasing rapidly. Finally, fixed wireless access systems are tempting for low population density areas (and sometimes for underdeveloped areas), where no fiber or copper infrastructure exists. In this paper we are not trying to give detailed analysis of the possible allocation of resources between digital TV and data communication services in LMDS. We concentrate on describing our novel two-layer LMDS network approach and give information on a trial system that was implemented and tested in Berlin in 1999.

1.1. CABSINET project

The CABSINET project (Cellular Access to Broadband Services and INtEractive Television) was a part of the Fourth framework research programme supported by the European Commission. Its original objective was to develop a system using both QPSK and COFMD modulation schemes for LOS and NLOS links and to carry out several trials for testing the viability of the LMDS communication system. The operating frequency of the final system is at 40.5–42.5 GHz following European frequency regulations by CEPT. The project was started in 1996 with the original plan to strictly follow the DAVIC standard and transmit all advanced services through ATM networks. As will be discussed later the project was abandoning a strict DAVIC and ATM compatibility, because our research and experience showed it to be suboptimal technology for advanced LMDS use. However, DAVIC [20–23] was followed in order to guarantee at least application level compatibility. In 1996 the competing (draft) standards such as IEEE802.14, IEEE802.16, DOCSIS and ITU J.112 did not exist. The CABSINET project was active until 2000. Extensive technology trials were conducted during the project, e.g. in Berlin (Germany), Rennes (France) and Oulu (Finland). At the time of the project development the two-layer LMDS network structure was a novel one. Recently we have seen that other groups and companies have followed this trend. This paper is an extension paper for Reference [3] with more in-depth description, results and better references to other relevant LMDS work done by other groups.

2. System Architecture

LDMS is a cellular radio system. Thus, it is composed of a Base Station (BS) and User Terminals (UT) that can communicate through a bidirectional link. We commonly refer to the link from BS to UT as *downlink*, while the UT–BS link is called indifferently as *uplink* or *return link*. The basic LMDS architecture has been a typical cellular architecture without hierarchy. One of the key issues in the CABSINET project was to introduce and test a two-layer network architecture. In Figure 1 we show a basic two-layer architecture we are proposing in order to enhance the usability of LMDS networks.

Macrocells operating at 28 and/or 40 GHz have a cellular radius of the order of 1–3 km. This forms the core infrastructure of the LMDS system. Macrocells

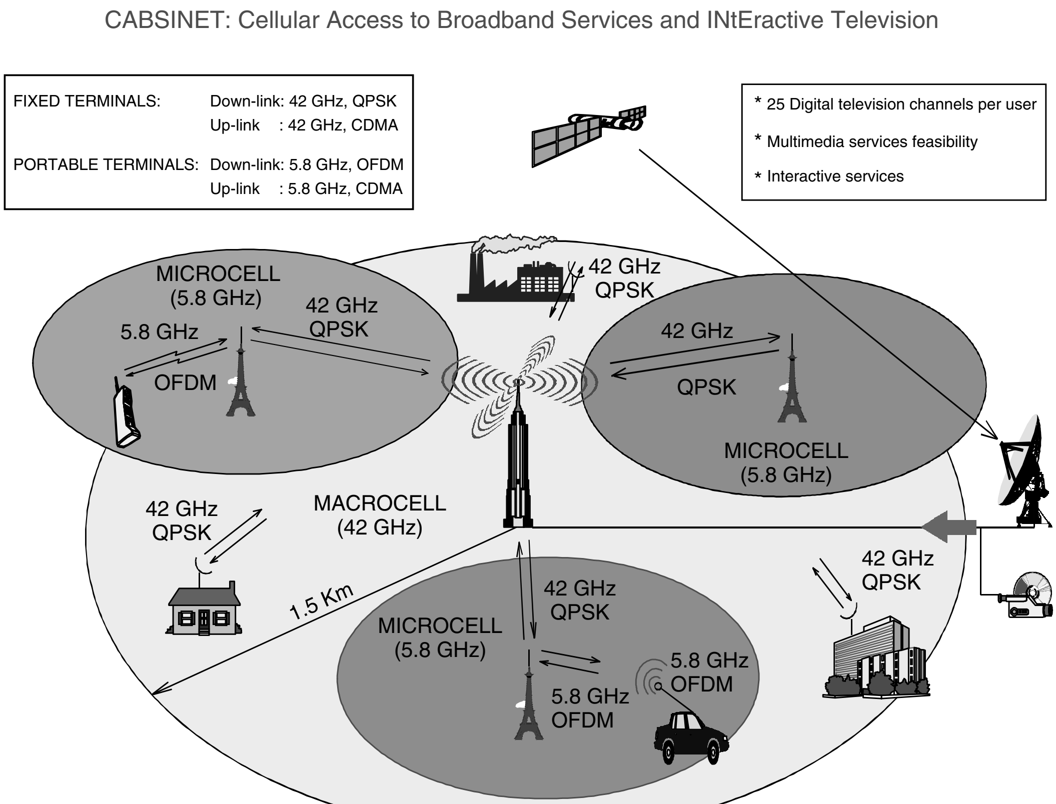

Fig. 1. The two-layer architecture for LMDS system includes higher frequency and capacity macrocells and non-line of sight microcells.

are further divided into microcells operating at lower frequencies typically at 3.5, 5, 10.5 or 17 GHz. The cell radius for microcells is flexible and can be of the order of 25–500 m. There are several advantages to this architecture. Traditional LMDS services in the 24–44 GHz band are suitable only for large high-rise buildings or in rural areas, where direct LOS links can be deployed. However, line of sight communication is not required at lower frequencies. Moreover, the end-user equipment can be less expensive and does not require a microwave dish antenna for reception. In the following discussion we will refer to our trial system using 40 GHz macrocells and 5.8 GHz microcells—the system could be developed and implemented for other LMDS frequencies too. One should understand that typically the total bandwidth available for microcells is smaller than in macrocells. Because of this, only a subset of macrocell transmissions can be used in each microcell. The macrocells are a kind of access network for microcells just like in HFC systems.

In Figure 2 we show the basic block diagram for the two-layer approach selected in the CABSINET project. It should be noted that users have two different access possibilities. First, one can use direct macrocell connectivity at 40 GHz, we refer to this as a fixed terminal (FT) access, as it requires a microwave antenna for connection. The second possibility is to have access through a microcell. This terminal option is called Nomadic Terminal (NT), because it can be freely moved within the microcell coverage area. We do *not* imply mobility, we just point out that a small antenna (like with WLANs) is included into terminal equipment. The frequency converter, or microbase station, that handles connectivity between macro- and microcells is called a local repeater (LR). In fact, the local repeater is a simple radio bridge with eventually some protocol logic, as it is explained later in this article.

2.1. Downlink transmission

Before going further into the details of the architecture, let us review the services that LMDS can support. LMDS was originally designed for digital television broadcasting, eventually including interactive

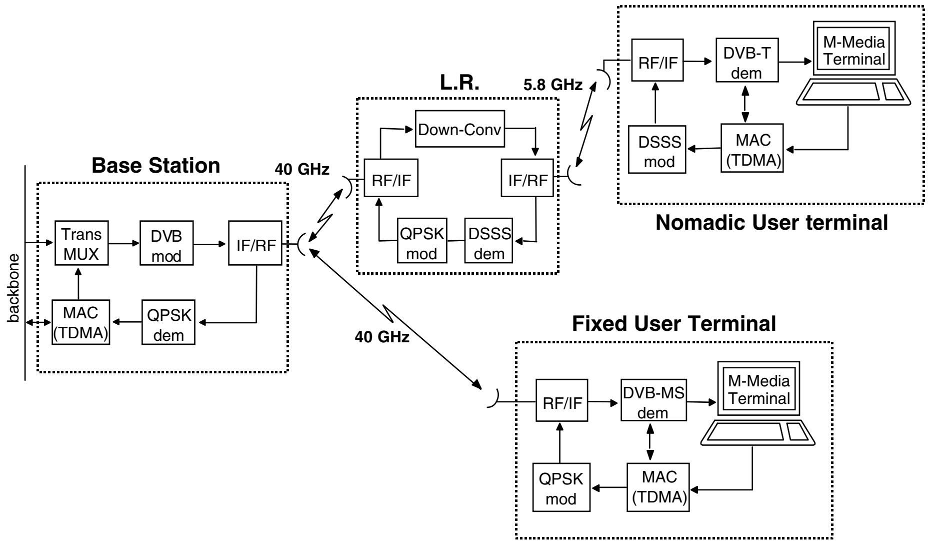

Fig. 2. General structure of CABSINET two-layer entities.

applications. This was envisioned to be the main applications by many early projects. In European Union ACTS R&D programme besides CABSINET there was also another project working with 40 GHz single-layer LMDS networking called CRABS [6–8]. Most recently, consumer interest has partially shifted from TV to Internet thus IP connectivity has to be supported as well. Finally, telephony would definitively complete this set of services, providing all services expected by most users over a single access network.

In the digital television industry, DVB standards are without doubt the most popular in Europe [9, 10]. The set of standards proposed covers the key parts of digital television professional and consumer equipment. Advantages of being DVB-compliant are obvious: LMDS can directly interface with any DVB compliant source at the base station, and commercially available set-top boxes can thus be used to display digital TV programs.

The DVB-S standard [22] by ETSI uses Quaternary Phase Shift Keying (QPSK) modulation for transmission. This is very robust against noise and non-linear distortions of amplitude. This modulation is perfectly suited for transmission at 40 GHz. The standard also proposes various combinations of bit rates and convolutional codes that makes it very flexible. Reed–Solomon forward error-correction is used as the outer coding technique. Up to eight erroneous bytes per MPEG-TS frame can be corrected, which increases reliability of the link

Figure 3 shows the frequency plan approved by CEPT (T/R 52-01). There are four groups of channels with a total of 96 channels in the band from 40.5 to 42.5 GHz. Linear polarization is used with the polarization of the groups 1 and 2 orthogonally with respect to the groups 3 and 4. Each polarization (and possible sectorial antennae) provides 48 channels with bandwidth of 39 MHz. Each downlink channel can transmit 34 Mbit s^{-1} for users. Because a single user or application rarely can fully use such a bit rate, several bitstreams are multiplexed into each channel. A typical configuration can be e.g. (a) four high quality MPEG2 TV-channels (4×8 Mbit s^{-1}) or (b) one high quality TV channel, two medium quality channels (2×4 Mbit s^{-1}) and 16 data transmissions each 1 Mbit s^{-1}. As one can see, the overall system bit rate within a single cell is in excess of

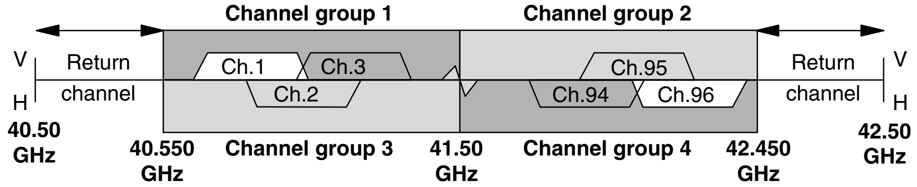

Fig. 3. Frequency plan approved by CEPT.

1 Gbit s^{-1}. In the case of CABSINET the combined bit rate of down- and uplinks with 90° sectorial antennas can reach 7.6 Gbit s^{-1}. Table 1 shows some key parameters of the CABSINET downlink.

Our Line-of-Sight (LOS) system follows the DVB-MS ETSI-standard with QPSK modulation, while the NLOS uses the DVB-T standard [11]. Both systems should have asymmetric interactive return channels. The DVB-MS is a cellular system with cells of about 3 km radius and the antennas of the user terminals must be located on the roof. It is useful only in the residential and rural areas since in urban areas the large number of shadow areas makes this kind of system unoptimal.[‡] A COFDM system may be more appropriate for urban areas because of its multipath properties [12]. The CABSINET project has demonstrated an operational two-layer network for LMDS [2, 3].

A base station broadcasts the channels in the macrocell in the 40.5–42.5 GHz frequency band to the fixed terminal (FT) and to local repeaters (LR) whose mission is to downconvert selected 40 GHz frequency channels to the 5.8 GHz band to be broadcasted to the nomadic terminals. The 5.8 GHz frequency band was used to give coverage to the microcell over an area inside buildings where the nomadic terminals are situated. The indoor propagation is of multipath type, this being the reason for OFDM modulation use. It is one of the best alternatives to counteract multipath effects in cellular communications [12].

The DVB-MS requirements for phase noise is −71 mm dBc at 10 KHz and, if just a single channel is transmitted by each power amplifier, there is no spurious intermodulation. The requirements of the DVD-T system are more restrictive and in order to provide a low cost solution, the architecture is based on a pilot tone with very low phase noise. This tone is transmitted by the base station. The LR uses this pilot to obtain a signal, estimate stability and phase noise of the pilot. Another problem of the COFDM system is the linearity of the power amplifier; it is a multicarrier system with about 10 to 12 dB between the peak and average power. Hence, a considerable back-off must be introduced or a very linear 40 GHz power amplifier developed. The project took the decision of utilizing a 10 dB back-off, this being the most cost-effective solution.

Table 1. The key parameters for CABSINET downlink.

Modulation	QPSK
Channels	2×48 or 2×32
Channel bandwidth	39 MHz
Bit rate per channel	34 Mbit s^{-1}
Multiple access	FDMA multiplex (TDMA optional extension)

[‡] With careful design and repeaters, it is possible to operate LOS systems in urban areas also.

2.2. Return channel

Our initial study of the return channel was focused on selecting an appropriate multiple access method from CDMA, TDMA or hybrid CDMA/TDMA. Because we are using a FDM/TDD-based down link and the number of users within a cell coverage area is large, we selected TDMA as the best MAC for LMDS. In principle, the CDMA based system could provide the same number of users, but developing a wide-band CDMA (W-CDMA) system with long spreading codes, and requirements for orthogonality, would have led to too expensive and complex a system. The scale of economy with LMDS systems is not comparable to mobile phones. Moreover, even the forthcoming third generation (3G) cellular mobile systems are using 5–20 MHz as WCDMA. In the case of LMDS we should support hundreds of users, and this would lead to either a system with a carrier bandwidth of about 50–400 MHz or multicarrier receiver architecture. We agree with Webb [5] that with broadband wireless application with several Mbits s^{-1} per user rates, CDMA is not economically viable solution for FWA/LMDS.

The return channel is based thus on a QPSK modulated TDMA system. The overall bandwidth for the return channel must be designed by the operator. Our estimates show that 100–400 MHz should be reserved for a return channel if TCP/IP data services are offered among TV channels. The return channel, as well as downlink, are using *in-band* signalling, i.e. signalling is embedded into ordinary data streams. The benefit of this approach is that there is no need for a separate signalling channel, and signalling structure can be easily extended through software upgrades during the evolution of systems.

The CABSINET uplink in trials were providing a 1 Mbit s^{-1} user bit rate over each 2 MHz narrowband uplink. This selection was done because our trials did not require larger capacity. We show key parameters for both nomadic and fixed terminal uplinks in Tables 2 and 3. However, we stress that larger bandwidth for each uplink channel is recommendable, because for each uplink channel we need

Table 2. The key parameters for CABSINET uplink from fixed terminal to base station.

Modulation	QPSK
Gross bit rate	2 Mbit s^{-1}
Convolution code	3/4
Channel symbol rate	1,33 Msymbols/s
Signal bandwidth ($\alpha = 0.3$)	1.73 MHz
Total user capacity	1 Mbit s^{-1}
Multiple access	FDMA/TDMA

Table 3. The key parameters for CABSINET uplink from nomadic terminal to local repeater.

Modulation	DSSS
Constellation	QPSK
Spreading factor	11
Gross bit rate	2 Mbit s^{-1}
Channel symbol rate	11 Msymbols s^{-1}
Bandwidth ($\alpha = 0.3$)	14 30 MHz
Total user capacity	1 Mbit s^{-1}
Multiple access	DSSS/TDMA

a separate QPSK receiver in the base station. The main difference between nomadic and fixed terminal uplinks is that the nomadic uplink at 5.8 GHz is using spread spectrum (DSSS) technology to fight against multipath.

2.3. Medium access and standards

Although a subset of the DAVIC standard has been adopted by DVB [9], there are a number of careful design issues to be solved in practical implementation. First, the DAVIC-standard has been initially designed for a cable system. Cable networks have very different characteristics in comparison with wireless environments. Extensions of the standard have been done in order to address wireless network specific issues. Nevertheless, some of the basic features of the system have been kept unchanged in order to provide backwards compatibility.

For example, the synchronization system for the uplink is working perfectly well on cable, but it is not adapted to a wireless link where the downstream signal can be lost for a short period of time. Moreover, DAVIC is based mainly on ATM. Unfortunately, ATM is rarely used in home computers. In fact, it is also losing its foothold in core networking. Instead, IP has taken supremacy and most consumer network applications are based on it. Since the system has to support IP, having an LMDS MAC based on ATM would increase the complexity of the system without bringing in any advantages except full compliancy to the DAVIC standard. It occurs to authors that, by trying to develop a highly flexible standard, the DAVIC committee finally produced a far too complex standard. This might actually explain why so few systems are implementing it.

For all these reasons, we believe that DAVIC is not the best choice for designing a MAC for LMDS-type network. However, its set of signalling messages gives a very good basis to work on and we therefore used a subset of DAVIC messages and some other interesting features to start our own MAC design. The result of this work is presented in the next sections of this article.

2.4. Services

DVB and later ETSI have addressed the need of transporting data over DVB networks. This standard [10], commonly called DVB-DAT, proposes several methods to broadcast different types of data. Among those, *Multi-protocol encapsulation* is the most suitable for IP and several commercial companies have implemented IP-to-MPEG gateways. As a return path, a PPP connection over phone line is commonly used, as are bidirectional connections through cable modems. In our case a full duplex customized wireless link layer had to be implemented so that IP-traffic was possible. As it will be shown later, this link layer has to ensure relatively low packet error loss so that TCP/IP can work efficiently.

Providing support for telephony over LMDS is technically challenging due to the different requirements that telephony has in comparison with video or data transport. However, if support for this service is part of the original system design plan, a simple solution might be achieved by re-using as much standard equipment as possible.

Recent interest for having integration of data and telephone networks have led to development of telephony over IP. Although, it would obviously not provide the most efficient design, it might very well be the most cost effective one. Caution has to be taken though: voice is sensitive to transmission delays. This is usually perceived as a late echo of your own voice when calling to a very distant ‘correspondant’. This problem might arise if the protocol stack implementation is too slow, which is likely to happen considering the stacking of voice codec, IP encapsulation and IP-over-MPEG re-encapsulation. Trial measurements of VoIP-over-MPEG end-to-end delay tend to show that system is feasible, but no detailed report has been published on this topic to our knowledge.

3. Multiple Access Control

At 40 GHz, a large bandwidth (typically tens to hundreds of MHz) is available for the return link. It would be unpractical to use it as a single wideband segment. FDMA is very appropriate as an outer multiple access technique. The bandwidth of each elementary channel is an important design parameter since it determines the total number of actual uplink channel as well as the maximum bit rate for a given modulation technique

Individual channels are shared between users with a time division multiple access (TDMA) scheme. This method requires that all transmitters share a reference clock as well as an *a priori* knowledge of the slot(s) each of them is allowed to use. From implementation point-of-view, such a system is relatively easy to build and design, ensuring the lowest possible cost.

Before discussing the TDMA frame format, the transport packet size must be known: since we are not using ATM in our system, there is no specific reason to use ATM-sized cells. Besides, transport packet size is an important optimization parameter. As previously mentioned, the DAVIC uplink packet format is ATM compliant. Since our LMDS network is using DAVIC compliant messages, our implementation is using this format. There was also an implicit drive in the project to be downwards compatible with DAVIC. As mentioned earlier, IEEE802.14, IEEE802.16 or DOCSIS were not available when the project went to the implementation phase [13–15]. Nevertheless, IP datagrams are much longer than an ATM packet payload. Hence, IP datagrams must be split between multiple transport packets. A longer packet size would lead to less fragmentation and consequently smaller processing and protocol overhead. This is a well-known problem with any IP-over-ATM or IP-over-wireless ATM system.

The optimum packet size depends on the statistical properties of transported frames among other limitations like FEC efficiency, memory size for buffering or channel fading characteristics. Clearly, determining the optimal frame length is difficult. Many factors have to be taken into account, for instance the value of the maximum transmission unit (MTU) parameter of the IP protocol stack. Nevertheless, an approximated or arbitrary solution can lead to very acceptable performance. The final adjustments can be done based on information collected from trials.

Using the MPEG2-TS format also in the uplink makes the link layer more homogenous so we performed a comparative study between the uplink packet size of ATM (payload 53 bytes) vs MPEG-TS packet size (188 bytes). However, it is important to note that, even if both are protected by Reed–Solomon FEC, their correction capacity is different: five correctable bytes over 53 for ATM and eight over 188 for MPEG.

The TDMA period includes 48 time slots in the trial setup of CABSINET network. This configurable parameter allows the choice of a suitable balance between throughput and end-to-end transmission delay. TDMA slots can be dynamically reserved and one user can use more than one slot (contention slots), if they are available. The key-parameters in the trial system were:

- Duration of inter-slot time margin (17 μs).
- Duration of the transmission of uplink frames (272 μs if 2 Mbps bit rate is used).
- Duration of the synchronization header (128 μs).

The TDMA configuration was developed only for the uplink in our test implementation. The downlink is using FDMA and multiplexing, i.e. there is a FDMA channel structure and each channel is multiplexed with several data streams that are identified by a header identification (ID) number. The downlink could use the same TDMA structure as the uplink. The need for TDMA in the downlink is a decision that must be made carefully. As long as there are lots of high bit rate connections and dynamic bursty data traffic is not over dominating network, there seems to be little to gain from introducing TDMA complexity in to the system.

3.1. Flexible TDMA framing

The most radical extension we have introduced for the DAVIC in our MAC-layer framing is the change of the frame structure in the uplink. We found out that the wireless system with large macrocells and unreliable links is more robust with the flexible and longer time-slot structure. This structure is shown in Figure 4.

There are several justifications for introducing this extension of the DAVIC standard. First of all, it allows a flexible TDMA structure (i.e. with k packets per slot and n slots per TDMA frame, n and k being integer numbers). This is required at first to accommodate different QoS (by allowing various frame lengths), and secondly to introduce an extra header (i.e. preamble) required for proper synchronization acquisition. Preliminary analysis of system requirements show that due to RF section frequency drift and

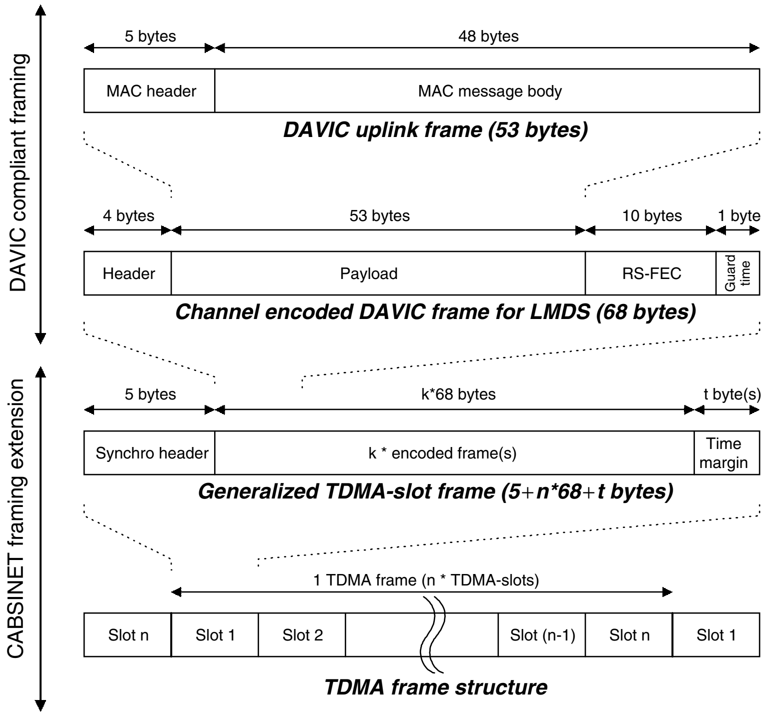

Fig. 4. Extended (eDAVIC) frame structure for more efficient communications and flexibility.

channel distortion, the uplink demodulator required a relatively long preamble to ensure proper burst acquisition. This phenomenon is also amplified by the fact that, because consecutive TDMA packets were originating from different terminals, the demodulator had to lock on the signals with different frequency carriers. The upstream definition the DAVIC version 1.2 is using fixed length TDMA frames (3–6 ms). As mentioned for large cellular size and for practical wireless RF-systems this frame duration is pushing the limits. The extended DAVIC frame structure can be used to eliminate this problem, and to gain better throughput. The drawback is that latency time increases and the system becomes slightly more complex.

This modification of the DAVIC standard provides a better use of radio resources and is completely modifiable through parameters. Our extended DAVIC (eDAVIC) framing structure is compatible with DAVIC both at the application and physical layer. Standard DAVIC applications will not see any difference. Moreover, setting $k = 1$ we can reduce the system back to full DAVIC compliance. If $k > 1$, physical layer compatibility is lost, but after packet recovery and rebuilding, the system provides normal DAVIC-compatible cells.

The *time margin* interval ensures that two consecutive packets (from differently located terminals) will not overlap because of propagation delay. DAVIC has addressed this issue by using a closed-loop synchronization system that allows a UT to compensate for this *a priori* unknown delay. However, the system is rather complex and costly to build. We prefer this simpler approach that requires minimal specific hardware (no time delay measurement nor compensation module) but which is more suitable for a wireless environment. Moreover, the DAVIC accurate synchronization system requires the extraction of the 8 KHz system clock from the downstream; this forbids use of commercial set-top boxes since extremely few equipment, if any, implement it. The synchronization is very similar to DVB/DAVIC approach. The signal frequency (network clock) of 8 kHz is rebuilt in DAVIC systems by using symbol clock *signal* of the downlink stream. We have chosen to use a *downlink MPEG2-TS byte clock signal* instead of network clock. The first advantage is that this method is part of every set-top-box, which provides access between the demodulator and MPEG2-TS demultiplexer. Another advantage of this signal is that it provides a direct time relation between uplink and downlink. Moreover, our solution is totally platform independent. We recommend this method for universal use to build synchronization clock signal in LMDS systems.

3.2. Comparison

The extended DAVIC compatible MAC protocol developed and implemented in the project works well, as can be seen by overall system level performance described in Section 7. As we mentioned earlier, there exists new related MAC recommendations and (draft) standards which have had a benefit from examining possible DAVIC problems. The most interesting are DOCSIS [13], IEEE802.14 [14], IEEE802.16 [15] and ITU J.112. DOCSIS, IEEE and DAVIC standards are very similar as all protocols are capable of parameter calibration and can assign frequency bands dynamically. All standards also support ATM-mode operation.

The main differences are summarized in the excellent paper by Ali *et al.* [16], and we follow discussion presented therein, but expand it to describe our extended DAVIC system. IEEE802.14 and DOCSIS are using minislots for contention purposes. DAVIC uses a contention slot with a size of an ATM cell (53 bytes with 15 bytes of overhead). The small minislots are very effective for bursty traffic or to optimize behavior with variable length packets from upper layers. In eDAVIC we do not have minislot structure available, but multiple ATM-cells lengths (in case of $k > 1$) can be used for contention. This makes the optimization for variable length packets possible, but for bursty traffic eDAVIC can be expected to be slightly inferior to IEEE/DOCSIS-based solutions.

Specific signaling commands between draft standards are different. IEEE and DAVIC have chosen to use *fixed length* MAC messages (single ATM cell), whereas DOCSIS is using variable-length messages. Our method is forced to follow DAVIC as we want to be backwards compatible, moreover we found out that the implementation of a fast MAC layer was easier for fixed length messages.

Our extended DAVIC protocol is using a ternary tree feedback mechanism as a contention resolution algorithm and ternary feedback messages are used (IDLE/COLLISION/NOCOLLISION) in the MAC. In Figure 5 we show comparative comparison between DOCSIS, eDAVIC and DAVIC approaches. As one can see with large packet sizes our eDAVIC performs well and is only slightly less effective than DOCSIS. Even today we feel that as we are using fixed length MAC messages and ternary tree feedback the system is quite well optimized. However, it is clear that the forthcoming IEEE802.16 standard will most probably be the main implementation guideline. We recommend that IEEE802.16 should be followed in future projects, as it provides a good performance and standards-track approach.

4. RF/IF subsystem

4.1. Intermediate RF stages the transmission

The definition of the IF and RF subsystems were done trying to fulfil the DVB-MS and DVB-T standards

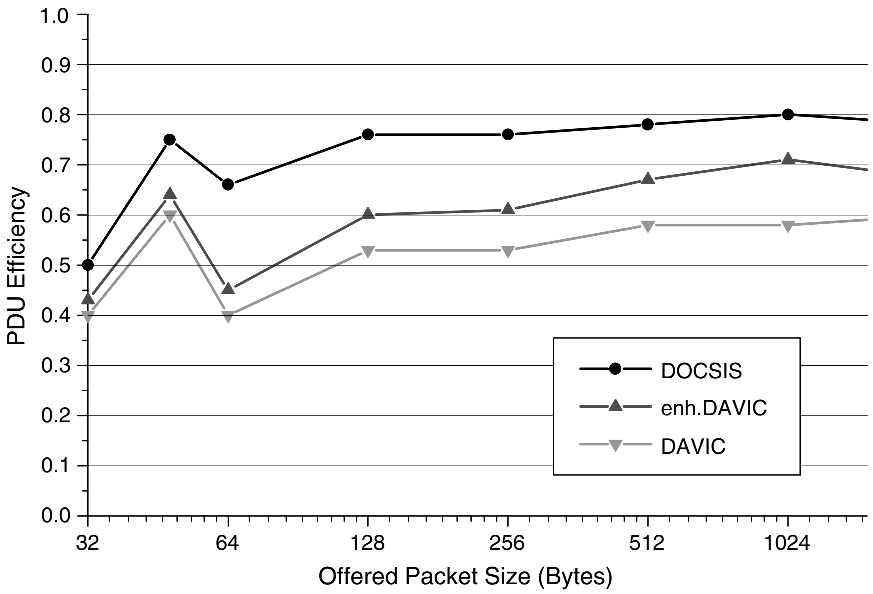

Fig. 5. Relative comparison between DOCSIS, eDAVIC, and DAVIC MAC schemes as a function of packet size.

completely. Figure 6 shows the frequencies that were chosen:

- The input and output of the modulators, QPSK, OFDM and DS-SS, are at 140 MHz.
- The second intermediate frequency is the frequency used in DVB-S, 950 to 2150 MHz, which makes possible the utilization of low-cost satellite receiver components, and applications.
- In the final stage, the almost 2 GHz are split into two sub-bands. This division has the goal of avoiding the interference between the emissions in adjacent cells. At the same time, each one of these two frequency intervals are subdivided into another two bands using orthogonal polarization.

We have reserved for the uplink of the trial system two bands of 50 MHz at opposite ends of each emission band. With the purpose of having enough guard band, the following combination is made: the users of the channel groups 1 and 3 will have the return channel in the upper band, while the cells belonging to the channel groups 2 and 4 use the return channel in the lower band. In this way, there is a guard band of 950 MHz in both cases. An actual production system probably should reserve more bandwidth for the uplink.

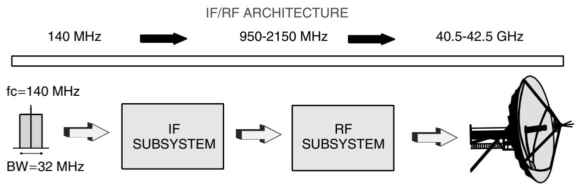

Fig. 6. RF/IF system architecture with selected frequencies.

4.2. IF subsystem

The same base station is equipped with two different IF converters, in order to transmit the QPSK channels to the fixed terminals or to transmit the ODFM channels to the local repeater, if required. Figure 7 shows the block diagram of the IF converter for the OFDM channels. The main difference between both converters is the pilot tone of the IF converter for the transmission of the OFDM channels. This pilot will be converted to the 40 GHz band and transmitted with the TV channels up to the UHF band of the local repeater, where it will be synchronized using a phase loop to minimize the distortions suffered by the information channels. Due to the pilot tone recovery in the LR, the signal recovers the phase noise and frequency stability of the pilot tone in the base station.

The channel will be formed at the input of the converter using a SAW filter. In this way, the mission of the highest frequency filter is to reject the interference of the local oscillator that appears within the bandwidth of the TV channels and as a consequence it must be a tracking filter in order to follow the channel of the local oscillator.

Furthermore, with the purpose of choosing the channel at the IF frequency band and to allow a fixed RF oscillator the design of a loop synthesizer at this IF frequency band is required. The phase noise of the different synthesizers are the following:

- Base Station: pilot tone, frequency: 41·5 GHz, phase noise: −76 dBc at 1 KHz

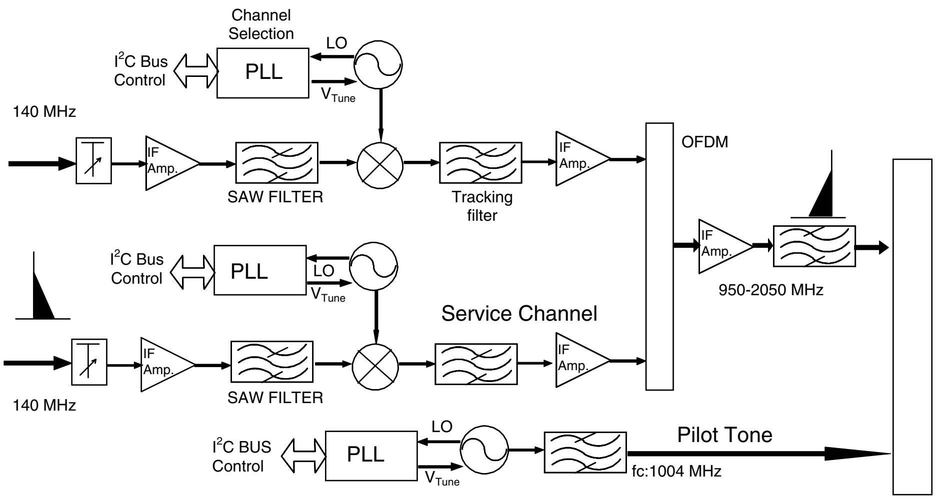

Fig. 7. Up-conventer for the OFDM channels.

- Local repeater: down-link upconverter, frequency: 5860 MHz, phase noise: −65 dBc at 1 KHz
- Nomadic Terminal: down-link downconverter, frequency: 5785 MHz, phase noise: −65 dBc at 1 KHz

4.3. RF subsystem

The block diagram of the RF subsystem is shown in Figure 8. With the purpose of taking advantage of other designs we have a ×3 multiplier in order to use oscillators in the 13–14 GHz frequency band that can be adapted from the designs already developed for satellite communications using the Ku band. The drawback of this solution is the phase noise degradation due to the multiplication operation: a 10 dB higher phase noise value is required to obtain performance similar to the direct approach. This increase in phase noise quality can be directly linked to an increase of cost. In this approach however, we can use a frequency divider having an input frequency in the 13 GHz band, far cheaper than a similar device working at 40 GHz as for the direct approach. Moreover, in order to make the cost of the PLO reasonable, a harmonic mixer with an external reference of about 2 GHz was used. Hence the design of the loop is relatively simple and cheap.

4.4. Transmission at 5·8 GHz

In the 40·5–42·5 GHz band, a 39 MHz of bandwidth has been reserved to broadcast four COFDM TV channels directly toward the local repeaters. Due to the fact that under the coverage of the same base station several of these local repeaters will be allocated and their cost will be a key point for the commercial success of the system, we have tried to increase the complexity of the base station in order to make the local repeaters cheaper. In this way the LR should have only the radio frequency equipment to convert the 40 GHz frequency band input into the 5·8 GHz band without any intermediate modulation/demodulation in baseband. One should understand that there are two different possibilities to implement local repeaters in our architecture, and these implementations can co-exist at the same time in the same network. The first possibility is the above-mentioned *frequency translation* LR. In this case COFDM modulated signal is transmitted and prepared already in the base station. The LR is simply downconverting from 40 GHz to 5·8 GHz. The advantage of this approach is that the LR is an extremely small and cheap unit. The second and more generic solution is that of a *protocol proxy* LR. In this case LR can tune in to any 40 GHz QPSK modulated channel. It does full reception, performs remodulation (with COFDM), and could even work as a protocol enhancement proxy. This leads to a situation where LR is very versatile and works like a mini-base station or access point. The disadvantage is increased complexity and cost.

As shown in Figure 9, in the 5·8 GHz band the available bandwidth is only 150 MHz, very narrow if a comparison to the 2 GHz available at 40 GHz is done. CABSINET has planned to transmit three groups of 39 MHz COFDM channels and a return channel of about 14 MHz within each microcell; this means there is about 13 MHz of guard band at 5·8 GHz between transmitter and receiver. A very

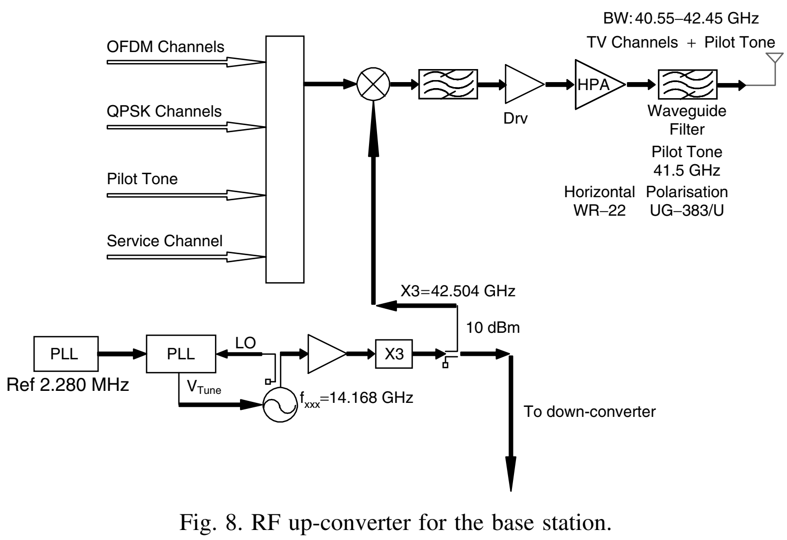

Fig. 8. RF up-converter for the base station.

narrow input filter is required to avoid saturation of the LNA.

Several possibilities have been studied to solve the problem. With the projected link budget about 60 dB of isolation has to be reached between the transmitter and receiver in both the LR and NT. If a narrow band circulator is used, the maximum isolation that can be achieved is about 40 dB, which it is not enough. Another alternative would be the use of two antennas with orthogonal polarization, but the achievable isolation is about 30 dB in the LR and about 10 dB at the NT side, because omnidirectional antennas must be used. Furthermore, the nomadic terminal is located inside buildings where you can not take advantage of this effect due to changes in polarization.

The last option was to use a filter built with resonators before the low noise amplifier. This solution provided enough isolation and, moreover, the losses in the bandpass in the prototypes had been of about 1 dB, which is an acceptable value for the noise figure. A mixer solution has been selected using orthogonal polarization plus a filter in the LR and two antennas plus a filter at the NT

Figure 10 shows the block diagram used in the down-converter of the nomadic terminal. The design has to be as cheap as possible and in this case we use an intermediate UHF band in order to simplify the design. The most important goal was to obtain a cheap 5·8 GHz oscillator fulfilling the OFDM phase noise requirements.

In Figure 11 we show the block diagram of the local repeater. For economy, converters already used in other systems have been re-used. For example, the converter for the return channel from 5·8 GHz to 140 MHz is equivalent to the up-converter of the nomadic terminal. The most important design is the 2 GHz oscillator that must be synchronized, using a phase locked loop, with the pilot frequency that arrives from the base station. This loop makes an improvement in the stability and, above all, is used to reduce the requirements of the phase noise of the RF oscillators by almost 20 dBc.

5. MAC requirements and performance

Prior to starting any system design, it is essential to summarize what functionality the system has to

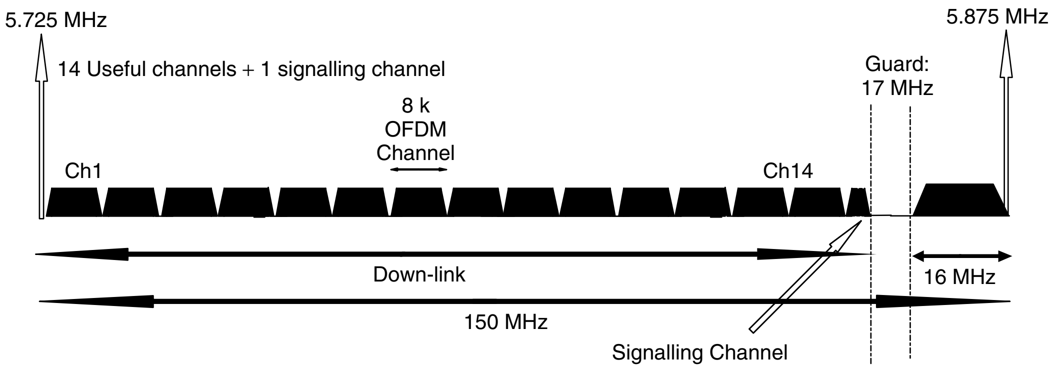

Fig. 9. 5.8 GHz channels arrangement.

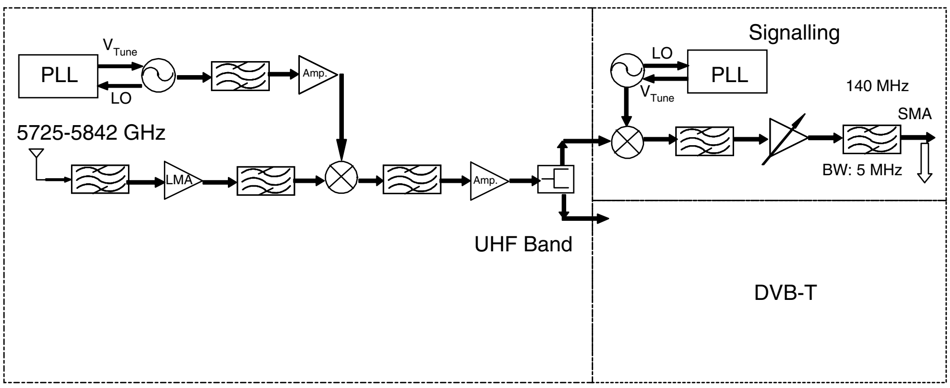

Fig. 10. Block diagram for down-converter of the nomadic terminal.

realize. In the following, we draw up the list of main requirements that must be fulfilled by the MAC layer of an LMDS-type system.

The primary function of the Medium Access Controller is to ensure correct transmission of information over a communication medium. In a cellular environment, the MAC has to handle identification and authorization, to boot-up terminal and then initiate a connection. Once the link is established, a MAC controls link reliability and responds accordingly to changes in environment or user requirements (setup of new service, attribution of more bandwidth etc.). In a cellular architecture, MAC tasks also include handling multiple access.

Since many application are generating bursty traffic, the system benefits from dynamic bandwidth allocation. However, due to asymmetry of the system and the broadcast nature of the downlink, only the uplink is providing dynamic bandwidth allocation in our *trial* system. Let us stress that dynamic allocation with TDMA contention slots can be provided in both directions if required. Bandwidth request, negotiation and (de-)allocation functions have to be implemented within the MAC. For this, some traffic control mechanism has to be combined with a suitably chosen resource allocation algorithm.

5.1. Performance metrics

For MAC performance metrics, we will focus on several key parameters that appear to be the most important for the services targeted. The first one we can mention here is throughput: this parameter defines the actual capacity one user can expect from the system. It reflects performance of the full link layer of the system and therefore is a reliable indicator of quality.

Another important parameter, especially for real-time services, is end-to-end delay. This parameter has a strong influence on the overall performance of the system, including throughput. Besides, it is directly perceptible by the user as system response time. An alternative parameter that could have been used is round-trip delay, but this would have less signification in our case due to system total asymmetry.

A wireless connection is inherently vulnerable to unauthorized access. Security might be an important issue for a LMDS network. Many existing off-the-shelf methods could be rather simply included within the MAC layer thus this specific issue is not addressed in this paper. Nevertheless, it is worth mentioning that the DVB standard, due to the broadcast nature of the downlink, has already addressed this issue.

5.2. LLC

A logical link control (LLC) has to ensure reliable transport of data packets over a link. Thus, it has to cope with lost packets and those that have not been corrected by the FEC block. In our design, both cases are handled identically: packets not corrected are dropped without attempt to recover any useful information. Especially, since the packet header does not have its own FEC, it cannot be used to try identifying the packet lost in order to request it again.

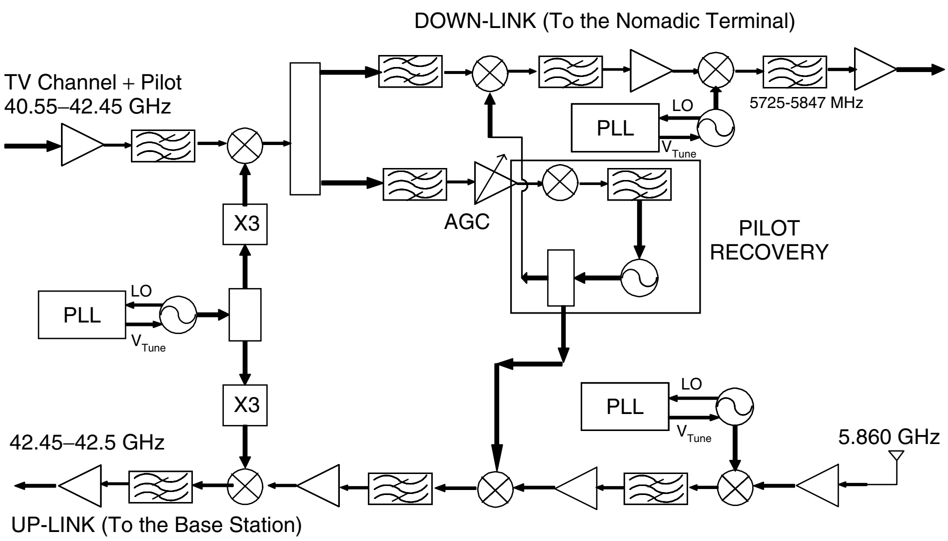

Fig. 11. Block diagram of the local repeater.

Naturally there are many different algorithms for LLC. The method we choose to implement is commonly called *Go-back-N*: up to N packets can be transmitted before reception acknowledgment is received for at least the first one. New packets can be transmitted as long as there are less than N packets not-yet acknowledged. The system can optionally report an error to a higher layer when more than K consecutive timeout occur.

This algorithm is easy to implement and does not require much memory. Besides, it is totally reliable and can be configured (by selecting carefully N, K and timeout period T) to suit LMDS transmission channel. Performance of the overall system using this algorithm is given below.

The second task of the LLC is to handle properly multiplex of services. For the downlink, this is quite straight forward thanks to MPEG-TS. One PID can be associated to each service (MAC, IP, telephony...). In the user terminal, demultiplexing can be handle very fast using dedicated ASIC.

6. Protocol Support for Applications

6.1. Service protocols

As we have stated the system is DVB and DAVIC compatible, hence all the audiovisual services specified through these standards can be supported through set-top-box into television. The original DAVIC version 1·2 envisioned that ATM services would be the underlying data network. We chose early in the project (in 1996) to differ from this opinion. Because of this, as we have described, ATM cell size is used on the uplink, but the downlink is using only MPEG2-TS frames for transmission. However, ATM cells can be embedded into the MPEG2-stream as described in DAVIC documents. Full ATM signalling is supported only to base stations, but ATM services can be sent to terminals. This was demonstrated successfully in a separate CABSINET trial in France.

Our main data transmission protocol is based on the UDP/TCP/IP protocol stack. As we have described earlier by using protocol embedding we can provide IP packets with full end-to-end connectivity for any terminal. In our trials a programmable set-top-box was used as the access point. In CABSINET the downlink to the customer is DVB compliant, i.e. we are multiplexing 188-byte-long frames into transmit streams in the base station. If we want to deliver MPEG-2 video, the corresponding traffic ID will be written in the header. Different IDs are reserved for IP-traffic, voice and ATM. In the customer terminal the MPEG2-TS stream is handled by the network interface, usually built into the set-top-box. The header ID is read, hashed and then decision for packet switching is made immediately.

- If the ID indicates IP traffic, we forward the packet to the IP-stack. Typically the packet is forwarded from the set-top-box to an output port (e.g. Ethernet, IEEE-1039) which is connected into a home network or computer.
- If the ID indicates digital-TV service (e.g. MPEG2 video), the packet is forwarded in to relevant codec in the set-top-box and subsequently into TV circuits.

Because we can multiplex several connections into a single MPEG2-TS stream, this means that a single user can receive *concurrently* both video and Internet connectivity. This has been successfully demonstrated in the project. We argue that this is potentially a very valuable feature, because then set-top-box and LMDS can work a universal access system both for audiovisual and PC applications.

6.2. TCP/IP over LMDS

There has been a large amount of work done towards developing and understanding TCP over unreliable wireless channels [17]. A large part of the recent work with wireless TCP is directed towards mobile cellular systems. There are some differences in the case of LMDS. Unlike other cellular wireless systems, there are no handoffs in LMDS. This eliminates the problem of handoff delays incurred in TCP. MobileIP and DHCP are good enough solutions for LMDS and micro-mobility solutions are not required.

The well-known problem is that wireless systems are susceptible to high bit error rates and large delays when compared to fixed systems. This has lead to more than suboptimal behavior of TCP over wireless. However, in the case of LMDS we can afford to perform aggressive channel coding. The interleaving, convolutional coding and Reed–Solomon code used (RS(204,188)), in practice, drop the link BER below 10^{-7}. Above this method our selective ARQ in LLC and finally TCP will provide very reliable link behavior. Overall LMDS networks are very suitable systems to deploy performance enhanced proxies (like the Berkeley snoop protocol [18]) because we know *a priori* that the last hop link is wireless.

7. System Level Performance

Now that we have presented most of the system modules, an example of overall system capacity can be given. Using standard DVB-S modulation in both uplink and downlink and having 40 per cent of available bandwidth (1 GHz assumed) reserved for the uplink. The CABSINET trial system was built in Berlin and test operations were done in spring 1999. This trial system was not a commercial trial, only a technology demonstration. Hence, only limited uplink (2 Mbps) and full downlink were established. In Figure 12, we show the base station room in Berlin where the test base station and measurement equipment were located.

Fig. 12. Experimental base station located in Berlin during technology trials.

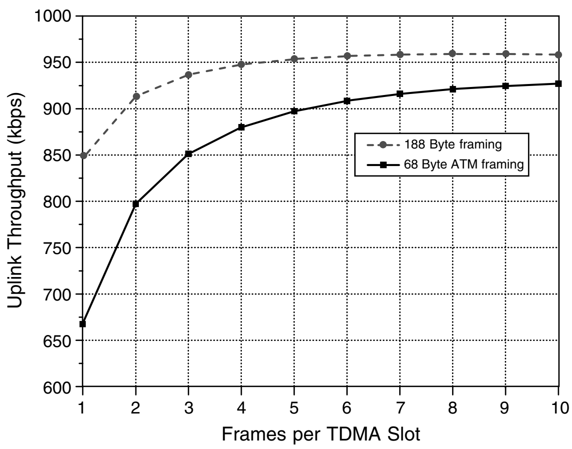

Fig. 13. Uplink throughput for different TCP fragmentation selections. Using an ATM-cell as wireless framing unit is suboptimal for TCP-over-LMDS. The upper and lower lines show results for 188-byte long MPEG2-TS frames and ATM-framing, respectively.

7.1. Frame size and fragmentation

The packet fragmentation in TCP-over-LMDS requires special attention. The size of IP packets are, of course, too long for wireless connections. Fragmentation at the MAC/LLC level is a bare necessity. The original DAVIC approach that would have lead to IP-over-ATM-over-LMDS would have been quite a suboptimal solution. The use of ATM is best justified only in the case of voice services. In Figure 13 we show the uplink throughput scalability for ATM framing (68 bytes per slot; 53 bytes for ATM plus extra radiolink headers and error control redundancy) against 188-byte frames. One can see that the longer framing length is more optimal for radio-link use, as expected. However, one should also note that when we are embedding more slots per frame ($k > 1$ in adaptive scheme) the difference goes asymptotically smaller. The maximum practical value for k is around 8, because of latency thresholds.

In Figure 14 we show how the end-to-end delay of data services goes up for some typical Internet services (HTTP and FTP), if the value of k is increased. The delay tends to go high after a threshold as the probability of packet errors is increasing.

The overall TCP delay includes the entire processing, including uplink delays. Especially in the case of asymmetric system such as LMDS, it does not scale linearly with downlink delay. In Figure 15 we show OPNET *simulated* performance (line) and measurements (points) for this. As one can see LMDS can provide a robust IP gateway for end users when the parameters are selected carefully.

Finally, we have to address the question of possible jitter and reliability with actual trials. In the case of

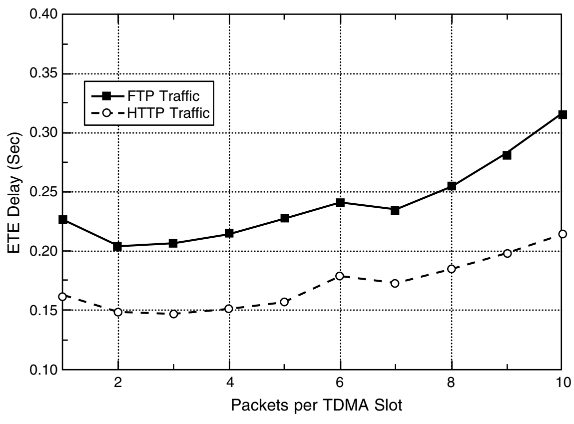

Fig. 14. End-to-end delay experience with applications as a function of frames (188-bytes) per each time-slot in two-layer LMDS system.

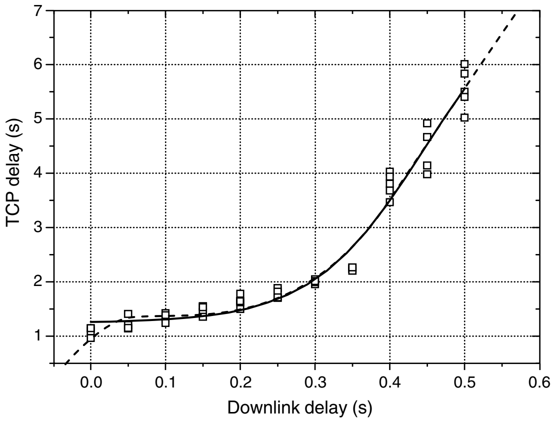

Fig. 15. TCP delay as function of downlink radio delay. One should note that this is not linear scaling.

MPEG2-video streams there is no noticeable jitter as they are sent as isochronous streams over a reserved channel. However, in the case of IP-services one can expect to see jitter. In Figure 16 we show the measured trace of round-trip time (RTT) for an ICMP echo message. This is done without any adaptive error control and one can see that most of the time RTT is constant. However, one can see from the trace that large peaks in RTT are occasionally generated because of lost packets and the time required to recover the situation. Using the Snoop-protocol in an actual production network is recommended as it would effectively fight against these error induced RTT-peaks.

7.2. Quality of service

The real-time guaranteed services (through the downlink) in our two-layer LMDS proposal are *not* based on related IETF proposals such as RSVP, DiffServ etc.). We have identified that most of the required real-time services can be delivered through reserved FDMA/multiplexed streams (like in ATM, if you get a connection you are guaranteed to get bandwidth).[§] Most of the services requiring real-time guarantee are anyway byte stream services like MPEG2 video, audio (MP3) or voice (ISDN/GSM). This solution takes full advantage of the fact that we can provide virtual circuit switching over an LMDS link. We suggest following (rough) service differentiation classes (note that we are not stipulating here how these traffic classes should be treated in the case of congestion):

- *Fully reliable, data throughput dominated services.* This is a traffic class where TCP is used with *maximal* possible channel coding. Out-of-order delivery is allowed
- *Real-time, non-error resilient services.* This is a traffic class where pure MPEG-2 stream transmission is used with reserved slots (or channels) and strong channel coding. In most cases this service is wireless video or television services.
- *Real-time, error resilient services.* This is a set of traffic classes where either (a) *reserved-slots* (channels) and weaker channel coding, or (b) UDP-over-LMDS is used. In our scenario the service is mostly voice, and voice codes are providing error resiliency.
- *Fully reliable, non-throughput dominated services.* This is like the first traffic class using TCP, but we rely more on TCP than channel coding to provide reliable transmission of data. The extreme bit rates are not an issue, hence errors can be tolerated and in downstream multiplexing this service might have lower priority.
- *Fully reliable, delayed data broadcast services.* A TCP-oriented service where data is transmitted out-of-order and only when there is extra bandwidth available. Typically this service is used to send software upgrades or downloads during non-peak-use time.

The extended DAVIC compatible LMDS system can provide good audiovisual and data services as can be seen from the results. However, there are some comparative weaknesses in DAVIC, which we want to report based on our experience. Firstly, DAVIC is a relatively complex standard and sometimes it is not easy to interpret. Secondly, the MAC structure and TDMA framing in the uplink was developed mainly for large request size and low contention load. The performance will degrade if traffic is mostly very dynamic and short requests dominate (e.g. a large number of Web requests). Dynamic slot allocation through the base station and the extended frame structure developed improves situation. However, the competition against DAVIC through IEEE and DOCSIS is, in our opinion, very formidable. It is still unclear what part of LMDS traffic is highly dynamic or bursty. In trial systems the latency through eDAVIC operations was acceptable for Web users, but the trials were done with low-to-medium contention traffic conditions.

[§] The question of how one guarantees or negotiates QoS between core network and base station is out of the scope of this article and LMDS design.

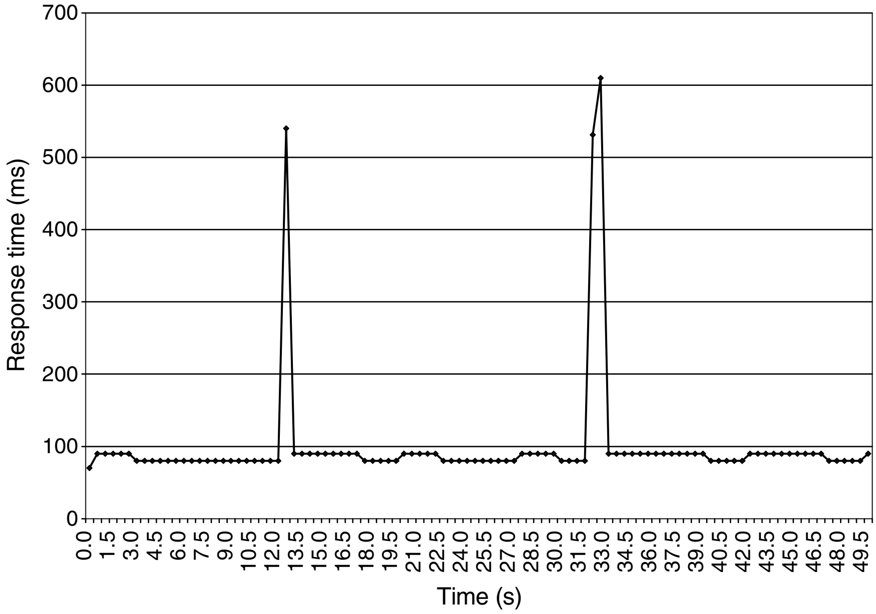

Fig. 16. Measurement of round-trip response time of an ICMP echo messages over trial network in Berlin.

8. Discussions and Conclusions

LMDS systems are well suited for fixed broadband wireless transmissions. We have argued and shown with practical implementation that LMDS networks can be used as platforms for both digital/interactive television and data networking. Moreover, we have been able to implement a robust TCP/UDP/IP delivery mechanism over LMDS. Our extension of single layer microwave LMDS into a two-layer network model also looks like a promising method to increase the usability of this wireless access method.

By replacing the proprietary microcell of the CABSINET system with better standardized technology such as HiperLAN/2 or IEEE802.11a would lead to a better utilization of LMDS as a broadband wireless backbone network. In fact, we did a limited testing in VTT Electronics in Finland (2000). In this demonstration the ordinary IEEE802.11b network was used as microcell extension for a household. The trial demonstrated that one can deliver a high-speed connection at 40 GHz to home set-top box and then deliver a video stream using WLAN and Internet.

We were able to confirm and extend previous studies (see e.g. Reference [5]) through practical implementation. Most notably we are able to state the following recommendations. First, LMDS systems should be seen as a part of a heterogeneous layered wireless network architecture. The high frequency part of the LMDS network is clearly just for access or broadcasting. Secondly, in most cases FDD is still the best-practice and TDD brings gains for operator only if highly variable asymmetric connectivity is required. Thirdly, it is clearly better to use single-carrier modulation schemes at higher frequencies. Our trial system was using simple QPSK at 40 GHz and was still able to provide very good bit rates. By migrating to QAM more effective systems can be built. OFDM is justified in lower frequency bands, but not at higher frequencies. One reason is that the peak/average ratio of OFDM is higher than in QPSK, and this is a serious problem for liner power amplifier design. Finally, we have shown that TDMA is still generally best suited for these high bit rate access networks [5, 19].

We argue that LMDS can be used both as broadcasting technology and as an integral part of emerging overlay networks infrastructure. One of the goals in the project was to study if LMDS can be made cost-effective enough for customers. The results were somewhat mixed. The overall expense for a single macrocell user is probably around US$1000 even with mass manufactured equipment. This is a bearable expense for professional (office) use, but a very high cost for the typical household. The cost structure is more tempting, if the household already has a digital set-top-box as a digital or satellite television receiver. Because of this we believe that when we are talking about typical consumers, LMDS and digital TV industries are somewhat interlocked to each other. Moreover, we feel that mere audiovisual services are not enough to get rapid customer acceptance for new technology like LMDS or digital-TV. However, if one can provide attractive service packs with games and transparent Internet connectivity for the PC, the situation is much better. Our main results and innovations can be summarized as:

- Two-layer LMDS system that can operate on several different frequencies.
- Extended DAVIC frame structure and MAC.
- Measurements and simulations of trial LMDS system in Berlin.
- Conclusion that DAVIC is complex. It is suitable for most purposes, but if low latency time for bursty traffic is preferred some other MACs are more promising.
- The demonstration that LMDS infrastructure can be used both for data and broadcast type services.
- We have shown that IP-over-LMDS implementation and interactive digital TV broadcasting can be coupled with packet switching networks.

Although our work has concentrated on LMDS technology, we believe that some of the results and recommendations are applicable also to the DVB digital television broadcasting industry. In fact, in a forthcoming paper we will be studying the interoperability and co-operation possibilities of LMDS and DVB-T networks and operators.

There has been a relatively small number of projects and research initiatives on studying LMDS as an integral part of the hierarchial overlay networking infrastructure. The situation is now rapidly changing and emerging standards such as IEEE802.16, HiperMAN and HiperACCESS will hopefully encourage more work on this front. Our own experience is that the LMDS systems operating in 24–43·5 GHz frequency bands can provide very good higher level infrastructure for wireless multimedia, TV and Internet services as access networks. It is clear that LMDS is not alone enough or economically viable, but when combined carefully with other technologies it is an interesting possibility. More research is required in this area which is overlapping between the broadcast and traditional wireless industry, including also requirement to transparently support standard IP protocols.

Acknowledgments

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