D D2.4 – FWA Feeder Solutions

Name: Gert-Jan Rijckenberg
Full address: DEN DOLECH 2, 5600 MB, EINDHOVEN, NETHERLANDS
e-mail address: G.J.Rijckenberg@tue.nl

Name: Anthony Ng'oma
Full address: DEN DOLECH 2, 5600 MB, EINDHOVEN, NETHERLANDS
e-mail address: A.Ng'oma@tue.nl

Name: Ton Koonen
Full address: DEN DOLECH 2, 5600 MB, EINDHOVEN, NETHERLANDS
e-mail address: A.M.J.Koonen@tue.nl

Identifier	Deliverable D D2.4
Class	Report
Version	V5
Version Date	16/12/2005
Distribution	Consortium/Public
Responsible Partner	TUE
Filename:	MUSE SPD D D2.4 v5.doc

DOCUMENT INFORMATION

Project ref. No.	IST-6thFP-507295
Project acronym	MUSE
Project full title	Multi-Service Access Everywhere
Security (distribution level)	Consortium/public
Contractual delivery date	30-09-2005
Actual delivery date	16-12-2005
Deliverable number	D D2.4
Deliverable name	FWA Feeder Solutions
Type	Report
Status & version	Final v5
Number of pages	33
WP / TF contributing	WPD2
WP / TF responsible	WPD2
Main contributors	TUE
Editor(s)	G-J Rijckenberg
EU Project Officer	Pertti Jauhiainen
Keywords	FWA Feeders, IEEE802.16, WiMaX, RoF, OFM
Abstract (for dissemination)	This document presents FWA feeder architectures developed in MUSE SPD and IEEE 802.16 protocol considerations. A summary of the first obtained results is given. The developed prototype was applied in a field trial conducted in Berlin

DOCUMENT HISTORY

Version	Date	Comments and actions	Status
0	26/09/05	Initial version	Draft
1	27/09/2005	First compilation	Draft
2	03/10/2005	Several edits	Draft
3	07/10/2005	Several edits	Draft
4	10/11/2005	Final draft	Draft
5	16/12/2005	Draft with processed comments	Final version

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In the MUSE project, various deployment scenarios, Access Platforms and First-Mile technologies are subjected to a number of studies. Subproject D focuses on high-speed access technologies that apply to FttX scenarios, where the available bandwidth per subscriber ranges from VDSL speeds (10 Mbit/s and up) to Fast Ethernet speeds (100 Mbit/s).

In deliverable D2.1 “First Mile Access Options”, an extensive overview was given of available and emerging technologies that to a smaller or larger extent meet these requirements. These technologies have been studied further in detail in SPD, and prototypes have been developed that were tested individually, as well as in integrated trials.

Among the mentioned technologies FWA is an important alternative when fibre is not an option. In deliverable D2.3 “FWA Feeder Designs” a concept for up-converting and distributing wireless signals by means of optical fibres, referred to as Optical Frequency Multiplication (OFM) has been proposed as a FWA feeder solution. OFM is a dispersion tolerant technique, which allows for very long optical fibre links (> 50 km) when compared to techniques which employ intensity modulation and direct detection.

In this deliverable DD 2.4, final FWA feeder architectures, component analyses and protocol considerations are addressed and the first results are presented. The FWA feeder has several cost related advantages: only low frequency RF processing devices are used; RAP installation is easy and maintenance costs are low which is important because of the large number of required RAPs, since cell sizes will be small at the employed high frequencies. The application of Software Defined Radio, a state-of-the-art radio interface technology, further simplifies the FWA feeder architecture.

The system was designed in accordance with the IEEE 802.16 requirements. Two different options are available. In the first option a low frequency signal is upconverted by the OFM processing to a suitable RF LO signal for the demodulation of received uplink signals. As such each RAP in a Point to Multi Point configuration can be assigned a specific frequency which prevents data collision in the upstream path. For the second option the data is put on a subcarrrier and the RF carrier is used as an RF LO signal in the RAP. Although less flexible with this option the Headend is less complicated.

Transparent transport over fibre lengths up to 25 km is demonstrated with data rates of 100 Mbit/s per channel. A relation was established between the QoS requirements in the MUSE project and the definitions in the IEEE 802.16 standard. High level component and network designs were performed for a point-to-point configuration.

The FWA feeder prototype was found to be well suited for application in the lab trial conducted in Berlin. Evaluation of this lab trial (DD2.5) involving the FWA feeder prototype presented here will become available at the end of Phase I of the project.

Some next possible steps are wireless measurements, MAC protocol design and the development of an interface to higher layers. These steps will make the system to evolve further so that actual service delivery becomes feasible.

LIST OF FIGURES AND TABLES

ABBREVIATIONS

ADSL	Asymmetric DSL
AGC	Automatic Gain Control
AGN	Aggregation Node
AM	Amplitude Modulation
AON	Active Optical Network
P/A-ON	Asymmetric Optical Network
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
CAP	Carrierless AM/PM
BPF	Band Pass Filter
BS	Base Station
CATV	Cable Access TV
CO	Central Office
CP(E)	Customer Premises (Equipment)
CWDM	Coarse Wavelength Division Multiplexing
DBS	Digital Broadcast Satellite
DMT	Discrete Multi-Tone
DP	Distribution Point
DSL	Digital Subscriber Line
DSM	Dynamic Spectral Management
DSLAM	Digital Subscriber Line Access Multiplexer
DVB	Digital Video Broadcast
DVD	Digital Video Disk
DWDM	Dense Wavelength Division Multiplexing
FCC	Federal Communications Commission
FDM	Frequency Division Modulation
FSAN	Full-Service Access Network
FttB	Fibre to the Building
FttC	Fibre to the Curb
FttCab	Fibre to the Cabinet
FttH	Fibre to the Home
FttN	Fibre to the Neighbourhood
FttP	Fibre to the Premises
HFC	Hybrid Fibre Coax
GSB	Global System for Broadband
HDTV	High Definition TV

HDSL	High-Data-Rate Digital Subscriber Line
MAC	Medium Access Controller
LO	Local Oscillator
MM	Multi-mode (fibre)
NT	Network Terminator
OADM	Optical Add-Drop Multiplexer
OFM	Optical Frequency Multiplying
OLT	Optical Line Terminal
ONU	Optical Network Unit
PC	Personal Computer
P2P	Point-to-Point
PDH	Plesiochronous Digital Hierarchy
PM	Pulse Modulation
PON	Passive Optical Network
POTS	Plain Old Telephone Service
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
SCM	Sub-Carrier Modulation
RF	Radio Frequency
SDH	Synchronous Digital Hierarchy
SDSL	Symmetric Digital Subscriber Line
SM	Single-mode (fibre)
SONET	Synchronous Optical Network
TFF	Thin Film Filter
VCSEL	Vertical Cavity Surface Emitting Laser
VDSL	Very-High-Data-Rate Digital Subscriber Line
VDSLoO	VDSL over Optics
WDM	Wavelength Division Multiplexing

INTRODUCTION

n the MUSE project various deployment scenarios, Access Platforms and First-Mile technologies are subjected to a number of studies. Subproject D focuses on high-speed access technologies that apply to FttX scenarios, where the available bandwidth per subscriber starts at VDSL speeds. First Mile Access Options are studied in detail in SPD, and prototypes are being developed that will be tested individually, as well as in integrated trials.

Among these First Mile Access options in the MUSE project is the development of a cost-effective system concept for high-capacity FWA (Fixed Wireless Access). FWA provides wireless communications between a fixed access point and multiple terminals. This system should enable wireless broadband service delivery at microwave carrier frequencies in access networks and in-house networks. Other target features are scalability in bandwidth and user density, the ability to reach at least 80% of the European citizens and the support for a cost effective migration of the bandwidth to 100 Mbit/s per subscriber by the year 2010.

In the previous deliverable DD 2.3, a general overview of the RoF based FWA system has been given. A concept for up-converting, and distributing wireless signals by means of optical fibres, referred to as Optical Frequency Multiplication (OFM) has been proposed. It involves interferometric FM-IM (Frequncy Modulation – Intensity Modulation) conversion of a frequency-swept optical signal in order to generate high-frequency harmonic components of the sweep signal. OFM is a dispersion tolerant technique, which allows for very long optical fibre links (> 50 km) when compared to techniques which employ intensity modulation and direct detection. The IEEE 802.16 standard has been selected to define the FWA feeder further.

A study which is related with the FWA study is BROADWAN. BROADWAN focuses at hybrid solutions for broadband access networks for fixed and nomadic users within a global coverage architecture. Radio over Fibre (RoF) is an example of a hybrid network and the MUSE FWA results could contribute to the BROADWAN objectives.

Another ongoing RoF project is GANDALF, which aims to demonstrate the simultaneous provision of Gbit/s data rates to wireline and wireless access nodes, by employing a novel optical feeder concept. This concept is based on a modulation sideband technique which is also known as the 2f method. The 2f method is like OFM based on harmonics generation which is a dispersion tolerant technique. In the 2f method one of the sidebands must be filtered for data modulation. With OFM this is not necessary.

In this report design issues are addressed for a prototype RoF system in a point-to-point configuration. Options are studied for centralisation of processing functions. The feasibility of OFM techniques for carrying microwave signals is investigated. In addition protocol considerations and high level component & Network designs are performed. Also Quality of Service (QoS) aspects of the IEEE802.16-2004 standard are addressed. MAC issues are considered as a preparation of a point-to-multipoint configuration.

This document presents also the first results that have been obtained. Evaluations of the lab trials (DD2.5) will become available at the end of Phase I of the project.

1 FWA FEEDER NETWORK ARCHITECTURES

One of the goals in the MUSE project is the development of a cost-effective system concept for high-capacity FWA. Such a system has been realized, and two options are proposed. This section gives an overview of the associated architectures and receiver structures. In addition the concept of Software Defined Radio is introduced to enable support of the IEEE 802.16-204 standard.

1.1 Overview of the OFM RoF system

1.1.1 The OFM principle

A novel technique to remotely generate RF signals is by OFM, which relies on techniques based on harmonics generation or FM-IM conversion. The downlink (DL) of the FWA feeder system employs the OFM principle. The technique has been outlined in [2], [3], [4] and [5] and is briefly described here.

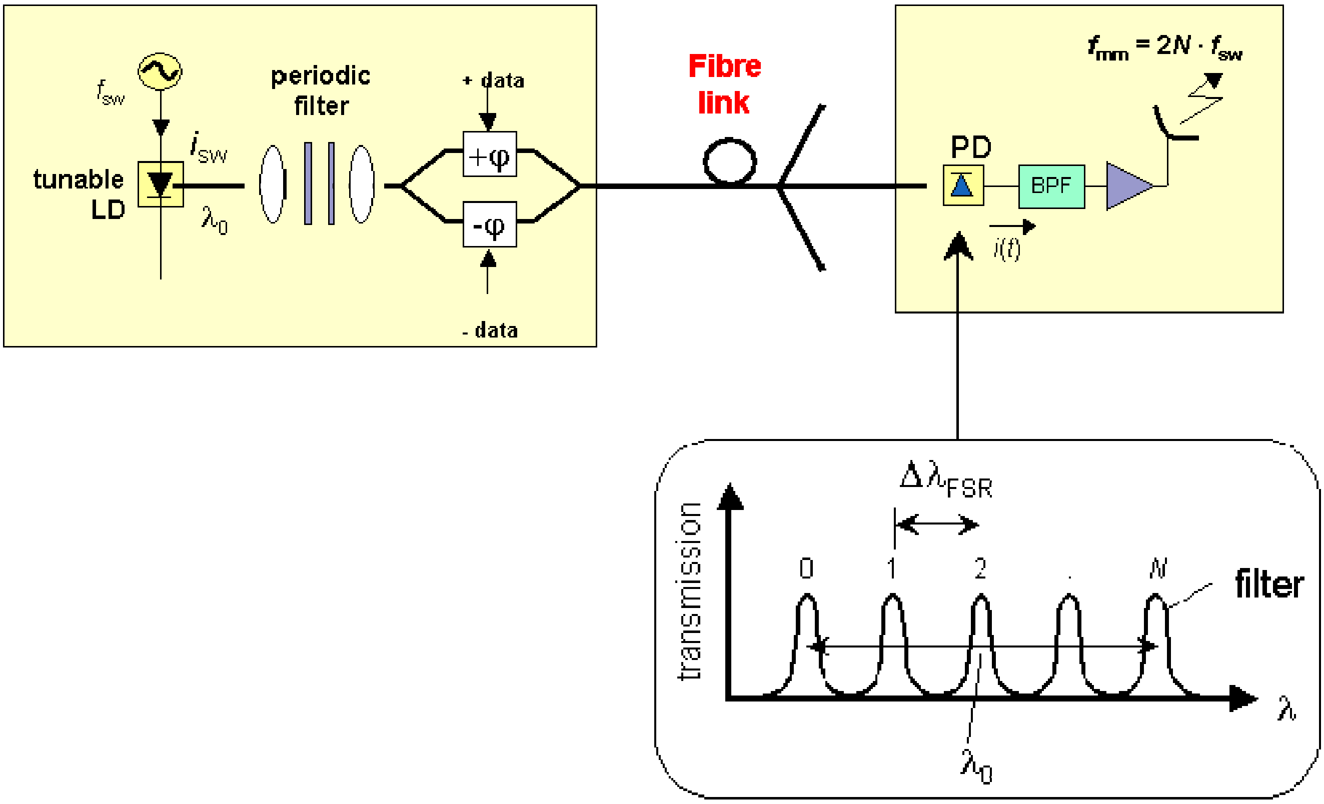


Figure 1 Schematic diagram of the OFM principle

In the OFM method, a low-frequency RF signal is up-converted to a much higher microwave frequency through optical signal processing. The system is based on an optical network, in which a laser diode is frequency modulated and a periodic optical filter with multiple equally-spaced pass-bands, as shown in Figure 1. The laser diode (λ_o optical wavelength) is modulated by a periodic signal (e.g. triangular) with sweep frequency f_{sw}. This signal is passed through the optical periodic band pass filter, whereas the data signal is inserted by modulating the light intensity [2].

The frequency modulated optical signal passes through the periodic optical Band Pass Filter (BPF) and then arrives at the RAP (Radio Access Point) where it is captured by a high-frequency photodiode. If the wavelength sweep of the signal ($\Delta\lambda$) is adjusted to encompass an integer number of passbands (which are separated by the Free Spectral Range (λ_{FSR})) of the optical filter, then each sweep of the signal generates intensity fluctuations at the photodiode. Consequently, microwave signals occur which are harmonics of the sweep frequency f_{sw}. The periodic optical filtering process does not affect the data intensity modulation (as long as the data rate is lower than the sweep frequency f_{sw}) and a transparent transport of the data signal is accomplished. An electrical band-pass filter after the photodiode suppresses the unwanted harmonics of the microwave signal, and reduces the noise. Subsequently, the signal is fed to the antenna, and the microwave signal carrying the data is radiated to the end user terminals.

1.1.2 The periodic band pass filter

Periodic filtering is achieved by using an interferometer whose response is characterized by multi-band pass transmission characteristics (refer to Figure 1). The Mach-Zehnder Interferometer (MZI), and Fabry Perot Interferometer (FPI) are some of the common filter types that may be used. Both types have their pro's and cons which are listed in Table 1. A practical solution can be obtained using a MZI with a Free Spectral Range of 10 GHz. For instance with a FM index $\beta \sim 5$ the 6th harmonic component at 17.202 GHz is at its maximum [4]. The electrical drive signal of the PM should then operate at a frequency $f_{sw} = 2.867$ GHz.

Fabry-Perot filter		**Mach-Zehnder filter**	
Pro's	Con's	Pro's	Con's
Easy to tune			Difficult to tune
	Difficult to integrate with laser (isolator)	Easy to integrate with laser	
Not polarization dependent			Polarization dependent
Contrast ratio depends on coating, easy to control			Limited contrast ratio
FSR easy to tune			Tuning is limited for active MZI and cannot be tuned for passive MZI
	Irregular sensitivity to laser λ - filter misalignment	Smooth sensitivity to laser λ - filter misalignment	

Table 1 Fabry-Perot filter versus Mach-Zehnder filter

Both filter types are available for the FWA feeder system.

1.1.3 The bi-directional RoF system

In a bi-directional system the DL and uplink (UL) can be realized by using two wavelengths λ_0 and λ_1 respectively, or by using two fibres with a single λ. A wavelength division multiplexing (WDM) device (e.g. using an interference filter) is used for transport over the fibre link of the up- and downlink signals. A schematic version of the bi-directional system is shown in Figure 2.

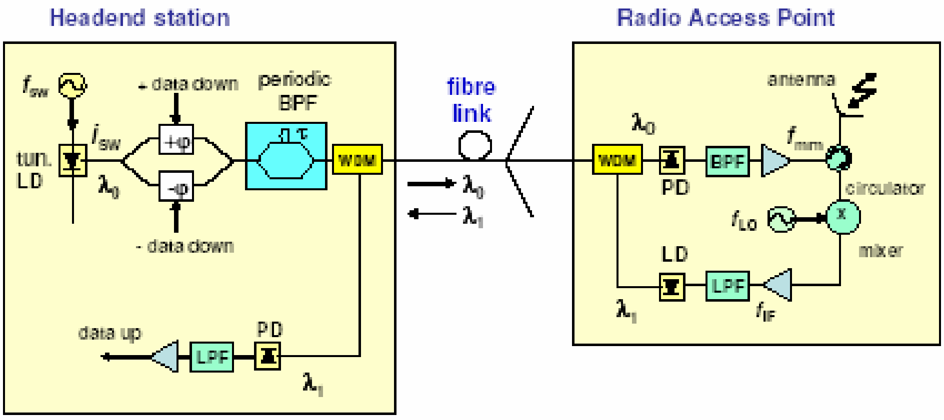


Figure 2 Schematic diagram of the RoF bi-directional system (from [4])

In the upstream path a LO (Local Oscillator) is used to down convert the microwave signal received from the subscriber terminal. The resulting signa is sent by direct intensity modulation of the RAP's laser at the upstream wavelength λ_1. The upstream is now at a frequency f_{if} which may vary per RAP to prevent upstream data collision in the Headend. More flexibility with regard to the LO can be obtained by remote delivery of a pilot subcarrier signal multiplexed with the downlink data signals. In this case, a low frequency pilot carrier is inserted at the headend and after the OFM upconversion to an RF tone, the remotely generated LO signal is selected after the photodetector. This solution is further described in Chapter 3.

The choice of IF is important for the final coherent receiver design as part of the bi-directional system. Two receiver designs are possible: *I* & *Q* demodulation and sampled IF. In the next section these options are further investigated.

1.2 Coherent receiver solution

Most modern receivers belong to one of three basic architectures: direct conversion architecture (zero IF), superheterodyne architecture with baseband sampling, and superheterodyne architecture with bandpass sampling (sampled IF).

From these architectures direction conversion is not an option because for instance ten-bit resolution can currently be realized up to 3.3 GHz [6] which is much too low for the employed frequencies (17.2 GHz). At the RAP direct intensity modulation of a low-cost laser diode is preferred, but its operation range is limited to relatively low frequencies. These considerations lead to a superheterodyne receiver architecture which is shown in Figure 3.

In the classical superheterodyne architecture the received signal spectrum is mixed down to baseband in two steps. During the first step, a high frequency LO_1 signal from a (tunable) frequency synthesizer is mixed with the RF signal, shifting the information signal to a fixed IF frequency. Then a fixed-frequency synthesizer at IF (quadrature oscillator) is mixed with the down-converted version of the received signal and finally shifts the *I* and *Q* signals to baseband. The accuracy of LO_1 is not critical, however, it should be stable and exhibiting a low phase noise. It is important to note that superheterodyne architectures can easily be implemented at very high RF frequencies.

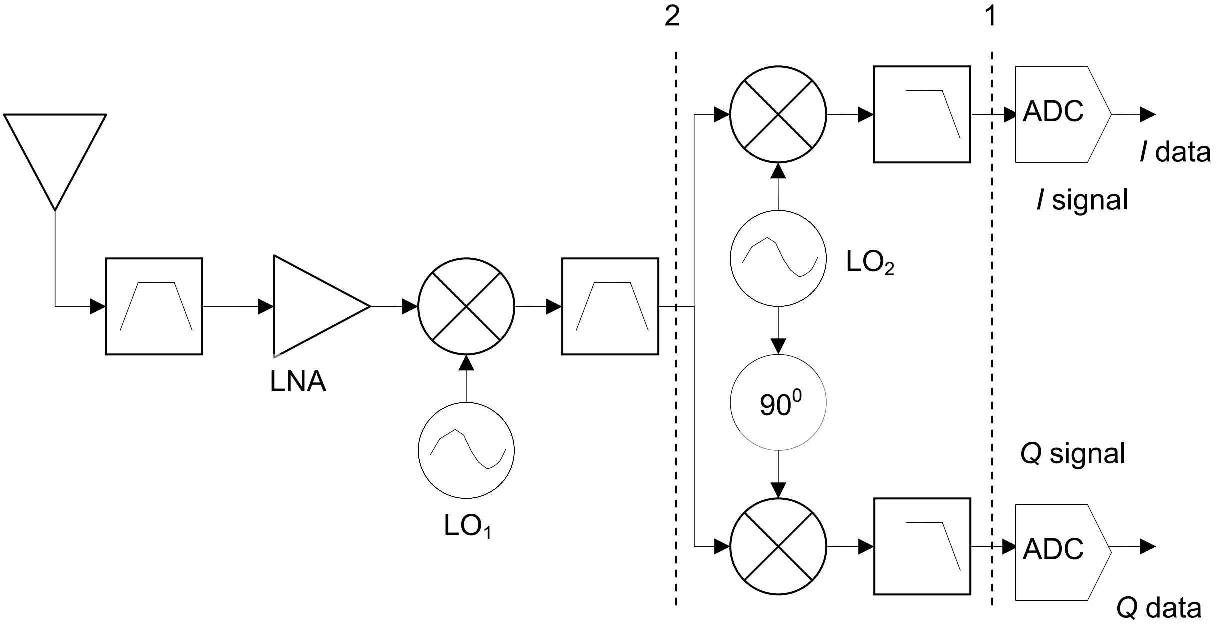


Figure 3 The classical heterodyne receiver architecture

Current receiver design philosophy is that the interface between the analogue and digital domains should migrate toward the antenna (in Figure 3, indicated with dashed lines, this corresponds to moving from 1 to 2). Following this line of thought, the conversion can take place after the IF stage with a single ADC. The advantage of this option is that the system no longer requires a pair of matched balanced mixers, matched filters, and a quadrature oscillator. These functions can be provided as DSP operations with significant performance advantages. When using undersampling techniques, high-frequency IF signals (typically > 100 MHz) can be quantified.

An example of such a design is illustrated by Figure 4. The received RF signal is down converted to IF and then after AD conversion, the baseband *I* and *Q* symbols are obtained through digital demodulation in the DSP. The configuration is often referred to as an sampled IF receiver, because sampling takes places at the intermediate frequency, before the quadrature down-conversion.

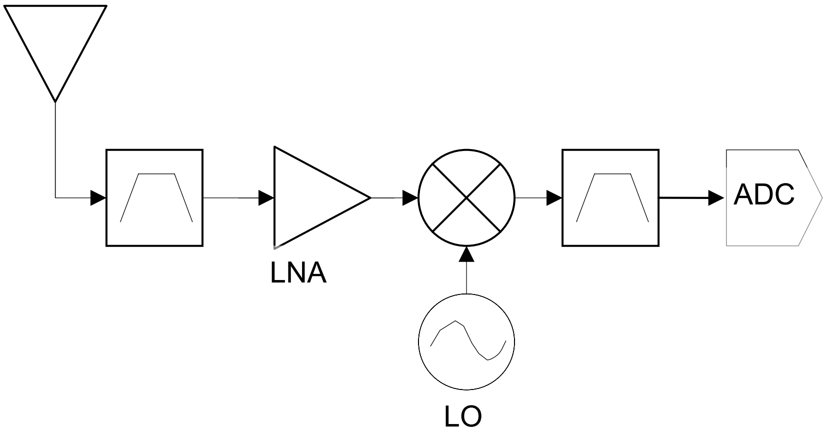


Figure 4 Sampled IF receiver

The process of channel selection and filtering in a sampled IF receiver can be achieved in the digital domain, thus avoiding additional RF/IF filter components. Furthermore, channel selection in a digital domain enables the realization of multistandard and multiband qualities of Software Defined Radio (SDR). SDR will be outlined in section 1.4.

It is noted that a filter before the mixer is necessary since spurious responses can corrupt the IF signal and cause it to be accepted as a valid IF signal by the IF amplifier. These spurious responses, alo known as images, are the result of power supply harmonics and intermodulation products, created during the mixing of the RF signal and the LO signal. This requires the use of a proper image rejection filter before the down conversion.

1.3 Centralization of processing functions

The physical layer of the RoF system is essentially composed of two sub-layers: at the top the conventional wireless layer and below the optical layer. The RAP has an optical interface only and without O/E conversion it is not accessible for any digital channels or base-band processing. This access point (with O/E conversion) is located at the headend. As a consequence the RAPs are virtually co-located at the headend. This property enables the construction of the simplest RAP, and most of the RF processing functions can be performed at the headend in the digital domain.

The following processing functions are recognized:

1. Radio link adaptation
    - Adaptive modulation

      i.e. change the modulation used by the transmitter in response to the changing channel conditions.

  - Frequency control
2. Phase recovery and Synchronisation
3. ADC/DAC
4. AGC
   please refer to section 3.1.1.2
5. Coherent detection
6. FEC (de)coding and Interleaving
   please refer to section 2.3
7. Duplex operation
   please refer to section 2.4
8. MAC processing
   please refer to section 2.5

Frequency control can be performed in the headend by tuning the parameters that drive the OFM process.

It must be noted that active control of DL power from BS transmitters is usually not employed. The BS signal is received by a variety of subscriber terminals, both near and far, and power control would tend to create an imbalance in the level of signals seen from adjacent sectors. Also in [7] it is concluded that a protocol should be invested in optimizing scheduling and rate adaptation, and not the power adaptation. On there other hand the BS must receive signals from subscriber terminals at different power levels. So in the UL power control is a necessity. In IEEE 802.16 a closed-loop power control for the subscriber terminal is defined: the BS measures the received signal and makes adjustment procedures by sending to the subscriber terminal information about how to adjust terminal output power. The output power level of the DL can be set statically, to the highest power level expected to be required in the worst weather conditions (as is mostly the case with conventional microwave radios).

At the headend a Digital Signal Processor (DSP) or Field-Programmable Gate Array (FPGA) can be integrated in the RoF system to perform the processing functions. DSPs, FPGAs and microprocessors allow analogue circuits such as filters, equalizers, and phase-locked loops (PLL) to be realized by signal processing into one chip, consuming a fraction of the power and area, and, therefore, lower costs. There are sophisticated signal processing algorithms such as convolutional encoding and interleaving available. It is obvious that this approach simplifies the headend hardware architecture considerably. The resulting transceiver architecture becomes very similar to a SDR system, which is described in the next section.

1.4 SDR and the RoF system

Though there exists no general consensus about the exact definition of SDR, the FCC has proposed to define SDR as a radio that includes a transmitter in which the operating parameters of the transmitter, including the frequency range, modulation type, and maximum radiated or conducted output power, can be altered by making a change in software without any hardware change.

SDR can be seen as a radio interface technology that generally consists of a software-reconfigurable hardware platform and software modules that enables flexible changes in the hardware platform for a specific radio system application. An SDR performs functions, e.g. down conversion, filtering, and demodulation, in the digital domain. The main limiting factor in software radio implementation is determined by current available data conversion technology since sample rates need to be as high as twice the signal bandwidth to keep the Nyquist principle.

The concept of “cognitive radio”, which seeks to make radio systems intelligent and adaptive to their environments, is a future goal for SDR systems.

Current SDR systems include an RF front end and an important constraint is the static bandwidth of RF components such as the power amplifier (PA) or low noise amplifier (LNA). Because of such limitations only a selection of similar standards is supported.

There are three reasons to consider SDR for the FWA feeder system:

1. SDR provides multi-standard support to a certain extent
2. WiMaX PHY processing requires a base station to be based on SDR [8]
3. With SDR processing functions take place in the digital domain with significant performance advantages

Some critical radio platform parameters that determine the performance of a software radio are given by Table 2.

Critical parameters	Remarks
Number of Channels	Number of parallel RF, IF and baseband channels
RF Access	Continuous coverage from a minimum to a maximum RF
Digital Bandwidth	Bandwidth of the maximum bandwidth ADC for each RF/IF channel
Dynamic Range	End to end, including RF, IF, ADC, AGC and processing
Timing Accuracy	Precision and stability of system clocks
Frequency Performance	RF, IF, and LO accuracy and stability
Processing Capacity	MIPS, MFLOPS
Memory Capacity	RAM, ROM per processor; mass storage capacity
Operating Environment	Operating system and related facilities, interfaces

Table 2 Parameters that determine SDR performance

An overview on trends and current available DSP and SDR technologies can be found in [9].

It is noted that multi-standard detection with wideband is also implemented in vector signal analyzers (e.g. FSQ40 from Rohde & Schwarz which has a sampling bandwidth up to 120 MHz).

1.5 Discussion

The presented RoF system supports a range of frequencies which are determined by OFM process drive parameters, such as the FSR of the periodic optical filter, the sweep frequency (which varies the optical frequency of the laser) and the multiplication factor N. Very little RF equipment is required at the RAP, which makes the system very cost-effective. In the UL (or receiver section) the sampled IF receiver is most suitable for the FWA feeder system. A single fibre can be used to carry both down- and uplink signals by employing WDM (refer to Figure 2, for DL a λ_0 ~ 1310 nm, and for UL a λ_1 ~ 1550 nm can be used).

The RAPs are virtually co-located at the headend. This property enables the construction of the simplest RAP, since most of the RF processing functions can be performed centrally at the headend in the digital domain, e.g. using a DSP. Frequency control can be performed in the headend by tuning the parameters that drive the OFM process. Power control is not defined in the IEEE 802.16-2004 standard power control for the DL (or transmitter section) [1], so it is not considered further.

SDR can constitute a major component of the RoF system. It allows for multi-mode operation in the receiver since its hardware can be reconfigured by software. The RF LO mixes the received signal down to IF, the I and Q demodulation takes place in the digital domain. In this way the strong requirements on the quadrature down conversion are relaxed. It is out of the scope of the MUSE project to develop an SDR. However, current test and measurement systems incorporate digital receiver structures which are similar to the described sampled receiver. So the application of SDR will be demonstrated in a way by means of actual measurements on the FWA feeder system.

2 IEEE 802.16 PROTOCOL CONSIDERATIONS

In this chapter an overview of the IEEE 802.16 protocol is given and QoS issues are addressed. Finally, the transparency of the optical link with respect to the IEEE 802.16 protocol is investigated.

2.1 The IEEE 802.16 standard

The IEEE 802.16 standard for broadband wireless access was first approved in 2001. The standard and its amendments define physical layer specifications for systems operating at frequency bands 2 – 11 GHz and 10 – 66 GHz, a medium access control (MAC) protocol and the convergence layers for carrying protocols such as IP, ATM and Ethernet.

An IEEE 802.16 point-to-multipoint system consists of a BS and one or more subscriber stations (SS). Duplexing schemes (i.e. the way the radio resource is divided between the up- and downlink) are either TDD (Time Division Duplex) or FDD (Frequency Division Duplex), with the FDD scheme there is support for half-duplex SSs. The transmissions in the DL direction are according to a TDM-like scheme, and it is possible to introduce so-called resynchronization preambles for the improvement of statistical multiplexing in a deployment with half-duplex FDD terminals. Half duplex FDD SS lose their phase synchronisation to the DL carrier and without the preambles an FDD SS must receive all DL data before transmitting. The UL is operating according to a TDMA-like scheme. In order to compensate link quality degradation between SS and BS, IEEE 802.16 utilizes a so-called “adaptive burst profile” in both UL and DL, meaning that the modulation type as well as the coding scheme is assigned burst-by-burst per subscriber station depending on the instantaneous channel conditions.

The IEEE 802.16 standard defines centralized and distributed scheduling mechanisms but it does not define a specific packet scheduling algorithm. A packet scheduling algorithm determines the UL and DL bandwidth allocation. So an important step in an evaluation of the IEEE 802.16 MAC protocol is the development and implementation of a scheduling algorithm, which is out of the scope of this study. It is noted that there will be no full duplex wireless measurements on the up- and downlink of the FWA feeder system, which would make an implementation of such a scheduling algorithm necessary.

The standard also specifies optional multiple antenna techniques like space-time coding (STC), beamforming using adaptive antennas schemes, and multiple input multiple output (MIMO) techniques.

2.2 The WirelessMAN-SC air interface

The 10–66 GHz air interface, which is based on single-carrier modulation, is known as the WirelessMAN-SC air interface. At frequencies below 11 GHz, the WirelessMAN-SCa, Wireless- MAN-OFDM and WirelessMAN-OFDMA air interfaces are specified.

Because of the high capacity requirement, the WirelessMAN-SC is most suitable for the FWA feeder system. It is designed for LOS operation at microwave and millimeterwave bands. A sector antenna is used for the BS and narrow beam antennas are used for the SSs. It is noted that the LOS requirement implies a truck roll installation, leading to higher costs for a subscriber. A truck roll means that a skilled technician with specialized test gear is required on site.

QAM 64 (optional), QAM 16 and QPSK modulation schemes are included in the WirelessMAN-SC air interface. As mentioned above the modulation scheme used in the air interface is related to the instantaneous channel quality. A high bit rate is then reached by utilization of broadband channels (20, 25 or 28 MHz). The high frequency of operation implies that radios can be fairly expensive, and currently, no vendors have announced products for this technology. However, in OFM mainly low frequency RF processing devices are used; RAP installation is easy and maintenance costs are low which is important because of the large number of required RAPs, since cell sizes will be small at the employed high frequencies. So it is clear that costs will become lower when compared to conventional radios.

2.3 Error correction

A digital communication system is designed to operate at a certain Bit Error Ratio (BER). A lower BER at a given LOS can be achieved by boosting the power of the transmitter, by increasing the receiver sensitivity and/or by adding Forward Error Correction (FEC) which enlarges the required signal to noise ratio. The error correction technique applied in IEEE 802.16 is based on Reed Solomon. Also convolutional encoding and interleaving are used to detect errors in order to improve the throughput. This coding adds redundant data that allows identifying and fixing bits that are missing or corrupted. The performance improvement achieved through coding makes it a very commonly applied technique.

Error correcting codes are judged by their coding gain. The coding gain is the ratio of the inherent gain of the error correction codes over its power penalty. The power penalty results from the need to send a larger constellation which includes the extra parity or check bits of the error correcting code.

The WirelessMAN air interface provides multiple coding schemes derived from combinations of GF(256) Reed Solomon codes and rate 2/3 convolutional codes. With such codes a coding gain up to 6 dB can be reached.

2.4 Duplexing scheme

In radio access systems there are generally two duplex schemes: FDD and TDD. IN FDD the up- and downlink are at separate frequency bands. FDD is suited for symmetrical traffic and long range systems. With TDD times slots are allocated to the up- and downlink which makes it very flexible. TDD has disadvantages such as the use of burst demodulators and synchronisation is more complex than with FDD. However, TDD is more suitable in the case of broad channels such as required in MUSE (28 MHz). In an FDD system the SS is usually designed to receive a continuous DL signal and it is possible that dummy data needs to be inserted when the traffic is low. This implies channels which are not too broad in order not to waste spectrum. On the other hand TDD allows for dynamically allocating resources according to e.g. geography, types of services and QoS.

2.5 The IEEE 802.16 MAC protocol

The IEEE 802.16 MAC protocol is connection oriented. Upon entering the network, each SS creates one or more connections over which their data are transmitted to and from the BS. Connections are either unicast or multicast for the DL and always unicast for the UL.

The MAC layer schedules the usage of the airlink resources and provides QoS differentiation. It performs link adaptation and Automatic Repeat Request (ARQ) functions to maintain a target BER while maximizing the data throughput. It is noted that the ARQ mechanism is not defined in the WirelessMAN-SC mode. The MAC layer also handles network entry for SS's that enter and leave the network, and it performs standard Protocol Data Unit (PDU) creation tasks. Finally, the MAC layer provides a convergence sub layer that supports ATM, cell- and packet-based network layers.

The MAC protocol is a hybrid protocol, based on a Demand Assigned Multiple Access (DAMA) mechanism. In the DAMA protocol the BS controls upstream data transmissions according to their QoS requirements. The BS collects all the requests from the nodes and requires scheduling algorithms to make bandwidth allocations.

QoS in IEEE 802.16 is based on the concept of service flows. Service Flows offer a unidirectional mapping between a SS and the BS. Each flow is represented by a unique identifier, to which bandwidth is allocated. An SS may have multiple service flows, with each flow utilizing a different scheduling service and set of QoS parameters.

In IEEE 802.16 the following flow types are defined:

- Unsolicited grant service (UGS), aimed for constant bit rate (CBR) for E1/T1 and VoIP without silence suppression
- Real-time Polling Service (rtPS) for VoIP or streaming video (MPEG) or audio services
- Non-real-time polling service (nrtPS) suitable for Internet access with minimum guaranteed rate.
- Best Effort

Traffic classes can be mapped directly onto QoS, i.e. each traffic class is served by a particular QoS service. Alternatively, several traffic classes can be mapped onto one QoS service so that the number of QoS services is less than the number of traffic classes.

2.6 IEEE 802.16 and QoS in MUSE

Current target of MUSE is to align with 3GPP and ITU-T QoS classes. In MUSE the loose QoS approach is adopted (e.g. Diffserv). The loose QoS approach is defined as a solution that provides soft or hard QoS guarantees by means of looser control mechanisms, which does not mean that the guarantees are loose. Table 3 lists the proposed traffic classes in MUSE [10].

Traffic class	**Max. burst size**	**Max. jitter target per node**	**Max. Packet loss rate per node**	**Max. load per link**
Low latency	200 byte	1 ms	10^{-10}	10%
Medium latency	1500 byte	30 ms	10^{-10}	50%
Elastic	9000 byte	900 ms	10^{-10}	40%
Best effort	-	-	-	-

Table 3 Proposed GSB traffic classes in MUSE

Best Effort class – For private Internet surfing, IP telephony
Elastic class – For professional applications, home office
Medium Latency class – For bulk video service, professional voice
Low Latency class – For special service, control traffic, low rate applications high margins

Integration of IEEE 802.16 with a loose QoS approach is possible if the IEEE 802.16 BS is equipped with a scheduling mechanism able to aggregate multiple incoming flows with similar QoS parameters into one single flow. The aggregation should be consistent with the different Behaviour Aggregates (BAs) as for instance defined by Diffserv in the core network. A BA is the collection of packets that have the same six classification bits, and which are crossing in a particular direction. A mapping of MUSE traffic classes onto the IEEE 802.16 QoS flows can then be performed as listed in Table 4.

MUSE traffic classes	**IEEE 802.16 QoS flow**
Best Effort class	Best Effort
Elastic class	nrtPS
Medium Latency class	rtPS
Low Latency class	UGS

Table 4 Mapping of MUSE traffic classes onto the IEEE 802.16 QoS flows

It is noted that in unlicensed systems, no QoS mechanism can be implemented. The spectrum is shared between all the systems operating at a given unlicensed frequency. In licensed systems, the service provider owns the only system operating over the allocated frequencies within a given area.

2.7 Propagation delay in the optical link

In a RoF system the additional propagation delay inserted by the optical link should be considered because it is not accounted for in wireless MAC protocols, although protocols have been developed which do take it into account [11]. Fortunately, IEEE 802.16 allows for dynamically controlling the propagation delay because the TDD framing is adaptive. A TDD frame contains one DL and one UL sub-frame and the bandwidth allocated to the DL versus the UL can vary. For FDD schemes the propagation delay is not an issue. In this section the TDD framing is investigated.

The TDD frame is divided into an integer number of physical slots (PS, 1 PS is the duration of 4 modulation symbols at the symbol rate of the DL transmission). The symbol rate is selected in order to obtain an integral number of PSs within each frame. E.g. with a rate of 25 Msymb/s, there are 6250 PSs in a 1 ms frame. The available bandwidth in the DL is defined with a granularity of 1 PS. The available bandwidth in the UL direction is defined with a granularity of 1 minislot (1 minislot consists of 2*m* PSs, *m* ranging from 0 to 7).

The Tx/Rx BS Transition Gap (TTG) is a gap between the DL burst and the subsequent UL burst. Similarly, the Rx/Tx BS Transition Gap (RTG) is a gap between the DL burst and the subsequent UL burst. During these gaps, the BS is not transmitting, allowing the BS to switch between transmit and receive mode. In the WirelessMAN-SC PHY both RTG and TTG should be no less than 2 µs in duration as defined by the minimum SS receiver performance [1]. The optical link delay can then be compensated by increasing the number of PSs that are assigned to the TTG and RTG parameters.

The compensation of the propagation delay is at the expense of a frame capacity reduction, which is linearly increasing with the fibre length. In [12] this reduction has been calculated as the ratio of idle PSs to the total number of PSs in a frame, for the 0.5, 1 and 2 ms frame types (as defined in [1]). For fibre spans shorter than 500 m, the reduction is less than 1% for the three frame types. With longer fibre spans, the differences are more noticeable: e.g. 8.8%, 4.4% and 2.2% frame capacity reduction results for the 0.5, 1 and 2 ms frame types, respectively, with a fibre span of 4.4 km [12].

With longer fibre links, the 2 ms frame type is more efficient in terms of utilisation of radio resources, because the ratio of idle physical slots to the total number of physical slots is lower than in the shorter frame types

2.8 Discussion

It is concluded that the IEEE 802.16 WirelessMAN-SC PHY specification is applicable to the FWA feeder system. In addition TDD is more suitable than FDD in the case of broad channels such as required in MUSE.

In the study no MAC scheduling algorithm has been implemented although this is a key step for a proper understanding of the desired QoS architecture. Nevertheless, a mapping of MUSE traffic classes onto the IEEE 802.16 QoS flows could be accomplished.

The optical delay introduced by the fibre link may become an issue with longer fibre lengths. However, IEEE 802.16 allows for dynamically controlling the propagation delay because the TDD framing is adaptive.

For point-to-multipoint configurations and inclusion of the wireless channel, it will be necessary to develop a MAC scheduling algorithm and to implement this algorithm in the headend.

3 A BI-DIRECTIONAL ROF SYSTEM BASED ON OFM FOR FIXED WIRELESS ACCESS

3.1 FWA feeder prototypes

This section addresses the design of the FWA system. Actually the OFM RoF constitutes the DL of the FWA system, for the UL or receiver the sampled IF receiver structure has been selected.

Two design options are proposed:

1) In the first option a low frequency signal (f_{shift}) is inserted in the headend and upconverted by the OFM processing to a suitable RF LO signal. At the RAP the upconverted data (f_{mm}) and remote LO signals ($f_{mm} + f_{shift}$) are separated by two BPFs. As such each RAP in a Point to Multi Point configuration can be assigned a specific frequency which prevents data collision in the upstream path.
2) For the second option the data is put on a subcarrrier and the RF carrier (at f_{mm}) is used as an RF LO signal in the RAP. At the RAP the upconverted data and RF carrier are separated by two BPFs. This option is less flexible because a subscriber needs to adapt to the RAP frequency which must be different for each RAP in case of a Point to Multipoint configuration. However, the headend is less complicated compared to the first option.

The two bi-directional system options are shown respectively in Figure 5 and Figure 6.

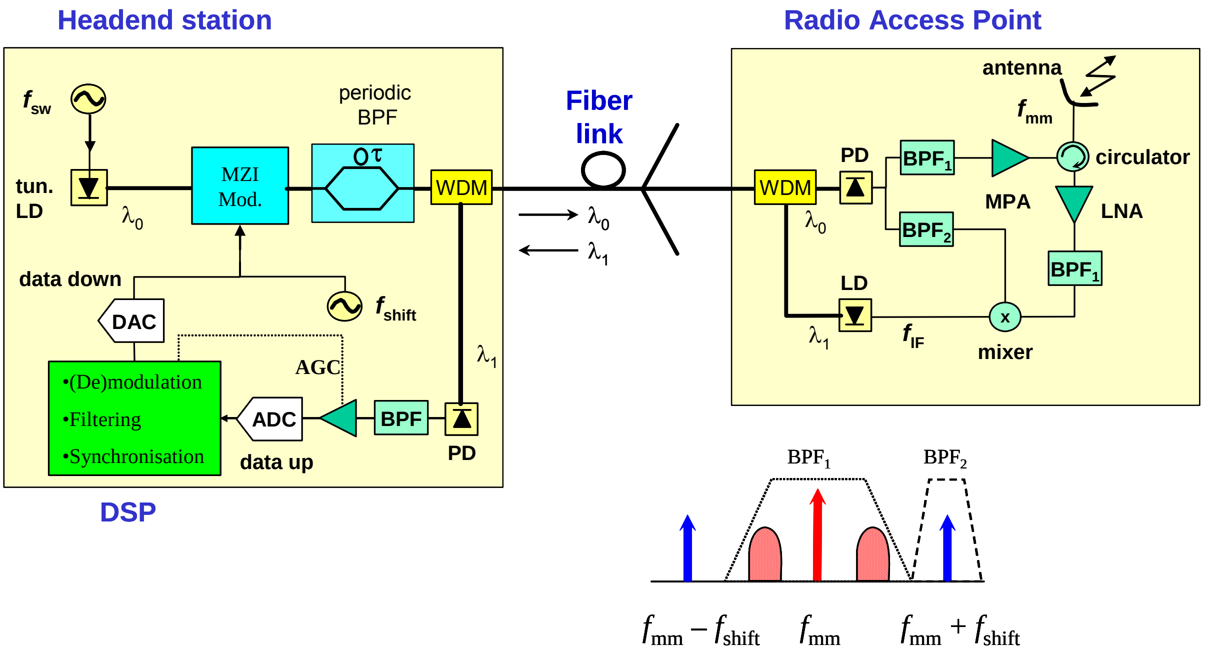


Figure 5 The bi-directional RoF system with remotely generated LO signal

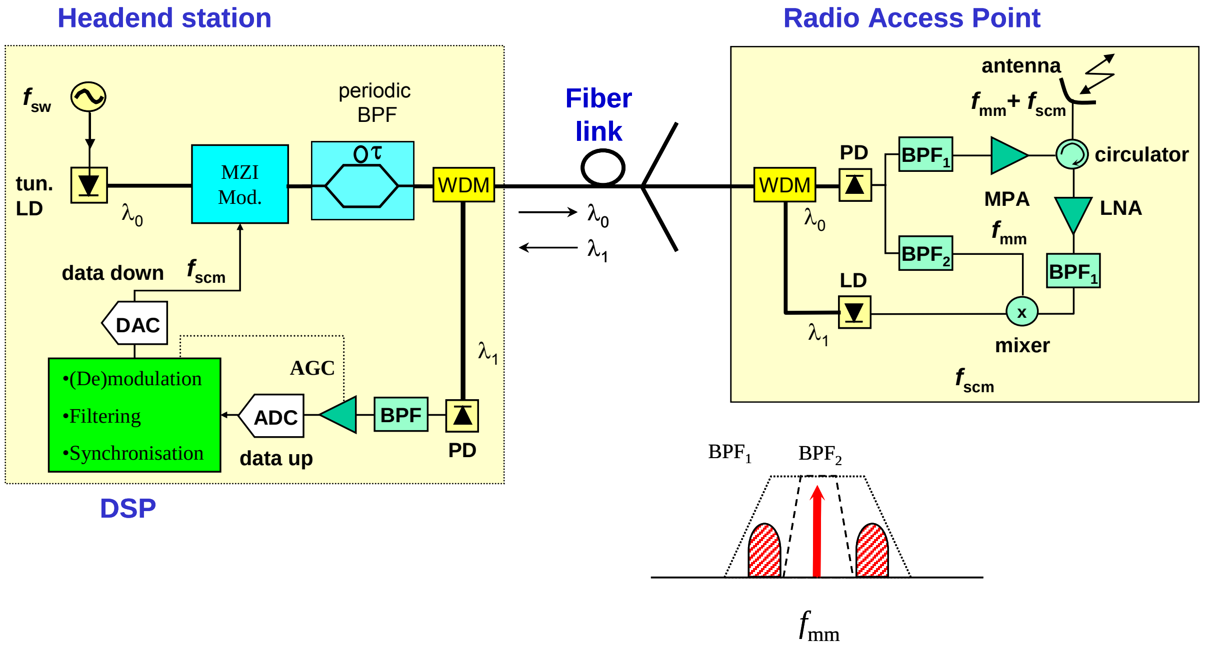


Figure 6 The bi-directional RoF system using RF carrier as LO signal

The next subsections describe the system in detail.

3.1.1 Headend

3.1.1.1 DL section

In the headend data is inserted in the optical DL and extracted from the optical UL. In addition the OFM process for generating the RF carrier at the RAP and a number of other processing functions are carried out in a data processing section. In option 1 also a LO signal is inserted in the intensity modulator. The DL and UL sections can be connected to a multiplexer/demultiplexer so a single fibre can serve for the transport of the UL and DL data signals.

Critical parts in the headend are the laser and the periodic filter. Since much experience is available for the MZI periodic filter [5], it has been used in the demonstration prototype. In general tuneable lasers are available for sweeping rates up to a few hundred MHz. In that case the OFM system would not be capable of supporting high frequencies because large multiplication factors and FM indexes would be required. For faster tuning speeds of laser wavelength, the use of commercially available phase modulators is a practical option. The phase modulation signal must be an integral of the desired FM signal. The DL section then consists of a CW laser (Distributed Feedback) operating at e.g. a wavelength 1316 nm, in combination with an optical Phase Modulator (PM), an intensity modulator (IM) and a MZI periodic filter.

3.1.1.2 The UL section

The UL section contains a photodiode and a data processing section that consists of both analogue and digital components.

Prior to A/D conversion, an IF filter is used to attenuate the LO and RF feedthrough and high frequency harmonics from the mixer. The IF signals can be digitized by a bandpass-sampling ADC with a high-speed, high-resolution, and low-noise performance. An AGC maintains the IF signal at a fixed level to the input of the ADC. The output of the ADC is then applied to the DSP. In the DSP the digital demodulator translates the waveform from IF to baseband and produces a demodulated output data stream and clock.

3.1.2 Radio Access Point design

3.1.2.1 DL section

In the RAP the DL RF signal is generated for transmission via an antenna. Both the DL and the UL sections are connected to a multiplexer/demultiplexer

The DL section consists of a photodiode (Schottky type operating at wavelengths 950 – 1650 nm), several RF BPFs, an RF amplifier, and via a circulator, the DL is connected to an antenna. Two BPFs are required for separating the downlink data from the remote LO signal (also a diplexer can be used). The center frequency and bandwidths of the BPFs are different for the two options as indicated in Figure 5 and Figure 6. For option 1 are used a BPF with center frequency at 17.2 GHz, and a bandwidth of 2 GHz (5EZ6 Lorch) and a BPF of 18.2 GHz and a bandwidth of 500 MHz (11WR42 Lorch). For option 2 are used a BPF with center frequency at 17.2 GHz, and a bandwidth of 500 MHz (10WR51 Lorch) and a BPF of 17.2 GHz and a bandwidth of 2 GHz (5EZ6 Lorch).

3.1.2.2 The UL section

The received UL RF signal is down converted to an Intermediate Frequency (IF).
For the down conversion to an IF the remote LO signal and a mixer (1 – 20 GHz, MARKY MW) are used.

The UL section consists of an RF and IF filter, an LNA amplifier (Cernex, bandwidth 0.5 – 18 GHz) and it is connected to an antenna via a circulator. A filter BPF_1 (17.2 GHz, bandwidth of 2 GHz, 5EZ6 Lorch) in front of the mixer stage serves as image rejection filter. A low cost laserdiode (λ_1 ~ 1310 nm) is amplitude modulated with the IF UL signals and via WDM the RAP UL section is connected to the headend UL section.

3.2 Specifications of the FWA feeder system

Several specifications from the IEEE 802.16 standard could be derived for the FWA feeder system. Table 5 lists these specifications. The optical wavelengths are chosen to be in line with the Joint Trial experiment in Berlin. An operating frequency of 17.2 GHz has been selected because a) this frequency is suitable for broadband FWA and b) because of existing experience at this range [5].

	Downlink	**Uplink**
Optical wavelength	**1316 nm**	**1310**
Optical power	**-3 – -10 dBm**	**Tbd**
RF Frequency	**17 .2 GHz**	**Depends on option**
RF Power	**20 dBm1a**	**NA (23 dBm1b)**
Modulation2	**QPSK and 16 QAM**	**QPSK and 16 QAM**
Roll Off	0.25	
Error control	FEC[3]	
Multiple Access	TDM	TDMA
Duplexing	TDD	
BER	$< 10^{-6}$	
EVM	12% (4-QAM); 6% (16-QAM); 1,5% (64-QAM)[4]	
Transmission range	5 km	

Table 5 FWA RoF specifications (specifications in italic bold were chosen, specifications in bold are requirements from the IEEE 802.16 standard)

1) IEEE 802.16 definition at BS[1a]/CPE[1b]
2) Adaptive; optional 64 QAM for DL and UL.
3) Reed Solomon GF or Block Turbo code
4) After equalization

3.3 FWA feeder measurements

Several measurements have been performed in the laboratory for both options. The EVM has been employed as the main performance measure. The EVM defines the average constellation error with respect to the far most constellation point power. In IEEE 802.16 it is measured over the continuous portion of a burst occupying at least 1/4 of the total transmission frame at maximum power settings.

Measurements on the FWA feeder system in a configuration according to both options are shown in Figures 7 to 10. The transmitter section in the RAP was directly connected to the receiver section. The Headhead and RAP were connected with two fibres (12.5 km and 25 km for the uplink and downlink respectively). Modulated signals were generated with a (Rohde & Schwarz SMU200) Vector Signal Generator (VSG). The applied modulation was QAM16 with a symbol rate of 25 Msymb/s, which corresponds with a data rate of 100 Mbit/s. A 40 GHz (Rohde & Schwarz FSQ40) VSA (Vector Signal Analyzer) was used to analyze the transmitted signals. The digital receiver of the VSA accommodates the processing functions which are centralized in the headend.

The open eye diagrams in Figure 7 and Figure 9 illustrate the feasibility of the system to transport data with low bit error rates. This is further supported by Figure 8, where an EVM of 4% has been obtained and by Figure 10 with an EVM of 5.5%. These values are well in accordance with the specified EVM of 6% by the IEEE 802.16 standard.

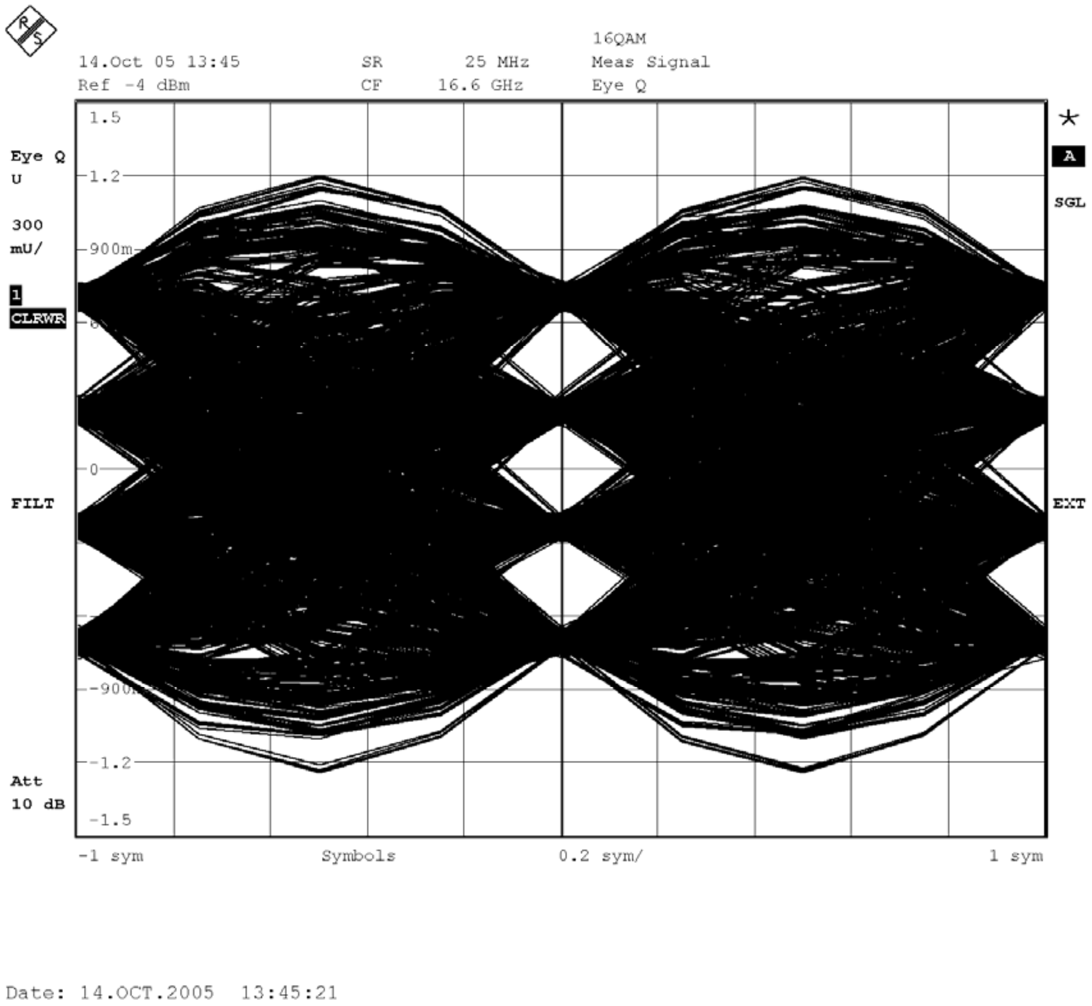
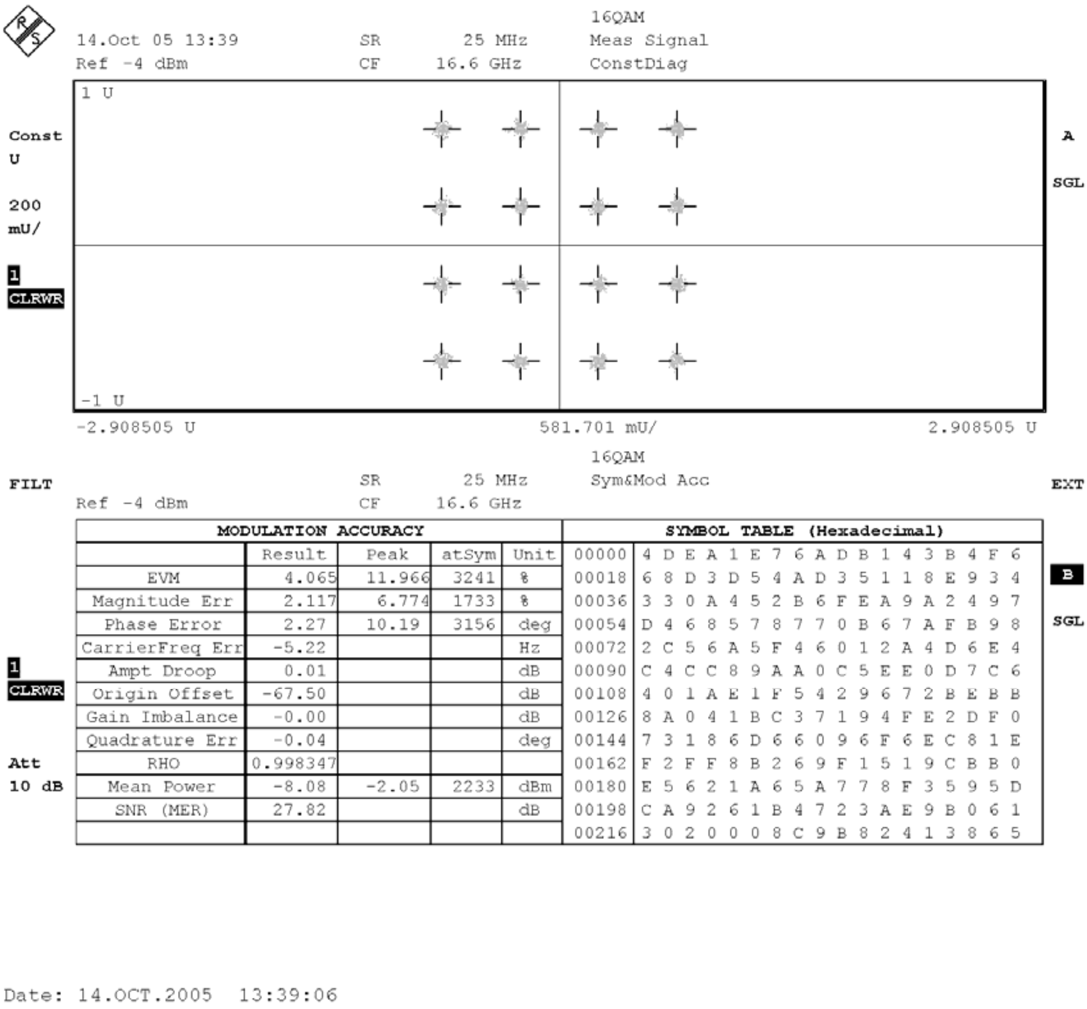


Figure 7 Eye diagram of option 1 for QAM16 modulation, with a symbol rate of 25 Msym/s



14.Oct 05 13:39   SR 25 MHz   16QAM
Ref -4 dBm   CF 16.6 GHz   Meas Signal
ConstDiag

-2.908505 U   581.701 mU/   2.908505 U

SR 25 MHz   16QAM
Ref -4 dBm   CF 16.6 GHz   Sym&Mod Acc

MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	4.065	11.966	3241	%
Magnitude Err	2.117	6.774	1733	%
Phase Error	2.27	10.19	3156	deg
CarrierFreq Err	-5.22			Hz
Ampt Droop	0.01			dB
Origin Offset	-67.50			dB
Gain Imbalance	-0.00			dB
Quadrature Err	-0.04			deg
RHO	0.998347			
Mean Power	-8.08	-2.05	2233	dBm
SNR (MER)	27.82			dB

SYMBOL TABLE (Hexadecimal)																		
00000	4	D	E	A	1	E	7	6	A	D	B	1	4	3	B	4	F	6
00018	6	8	D	3	D	5	4	A	D	3	5	1	1	8	E	9	3	4
00036	3	3	0	A	4	5	2	B	6	F	E	A	9	A	2	4	9	7
00054	D	4	6	8	5	7	8	7	7	0	B	6	7	A	F	B	9	8
00072	2	C	5	6	A	5	F	4	6	0	1	2	A	4	D	6	E	4
00090	C	4	C	C	8	9	A	A	0	C	5	E	E	0	D	7	C	6
00108	4	0	1	A	E	1	F	5	4	2	9	6	7	2	B	E	B	B
00126	8	A	0	4	1	B	C	3	7	1	9	4	F	E	2	D	F	0
00144	7	3	1	8	6	D	6	6	0	9	6	F	6	E	C	8	1	E
00162	F	2	F	F	8	B	2	6	9	F	1	5	1	9	C	B	B	0
00180	E	5	6	2	1	A	6	5	A	7	7	8	F	3	5	9	5	D
00198	C	A	9	2	6	1	B	4	7	2	3	A	E	9	B	0	6	1
00216	3	0	2	0	0	0	8	C	9	B	8	2	4	1	3	8	6	5

Date: 14.OCT.2005 13:39:06

Figure 8 Constellation diagram of option 1 for QAM16 modulation, with a symbol rate of 25 Msym/s.

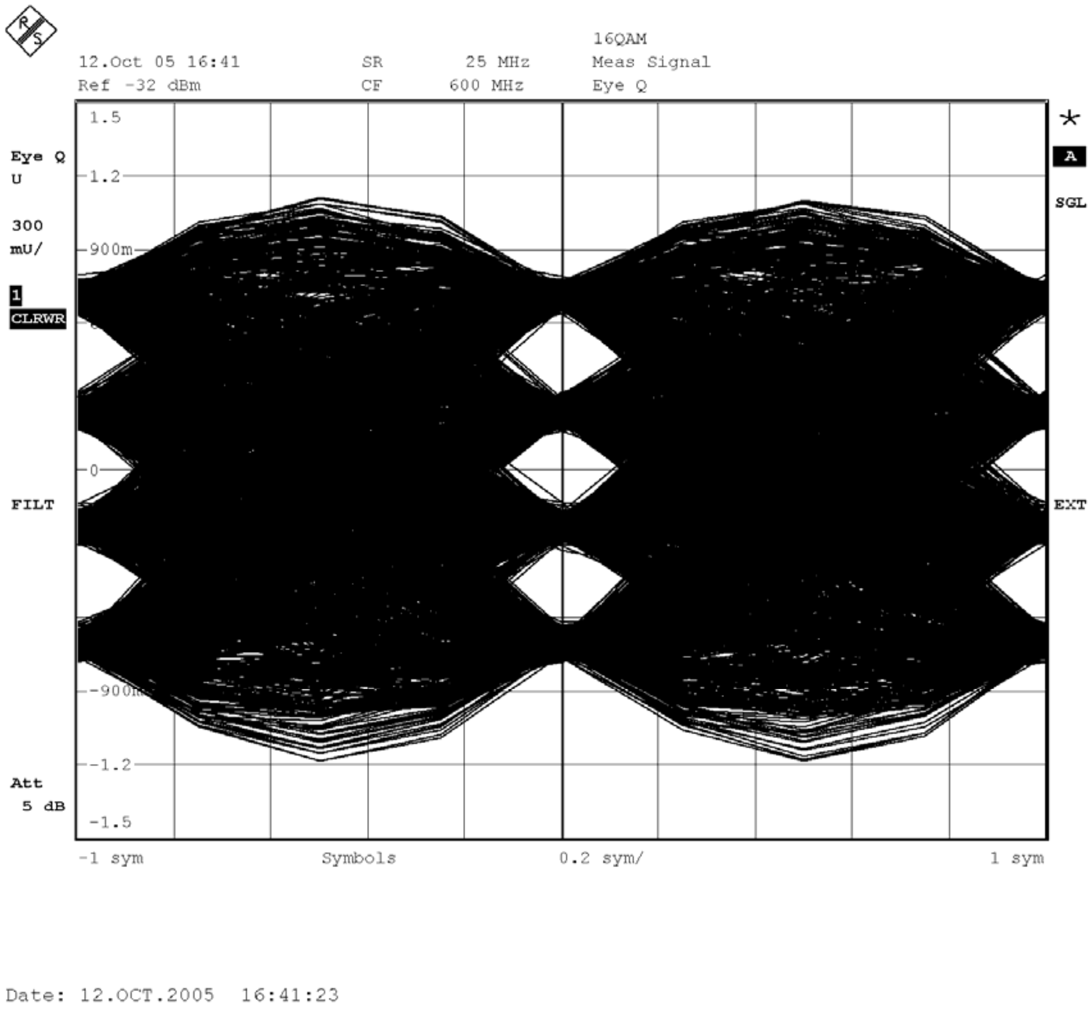
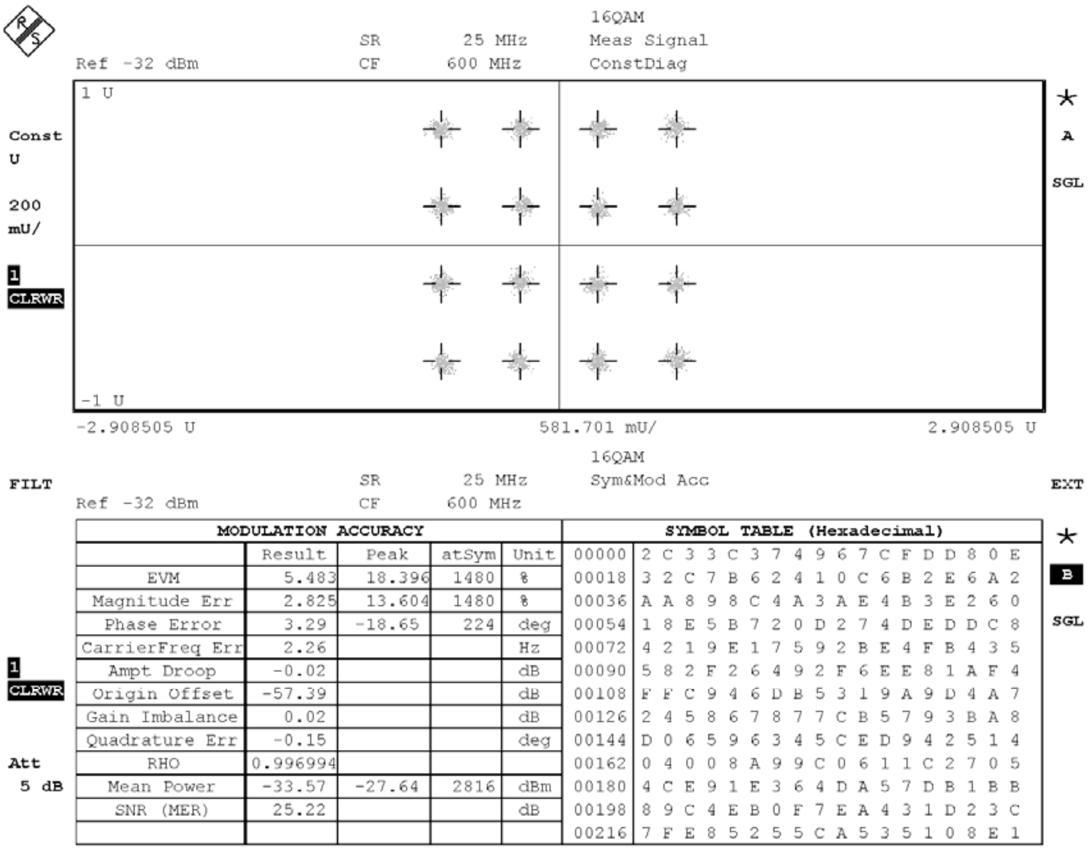


Figure 9 Eye diagram of option 2 for QAM16 modulation, with a symbol rate of 25 Msym/s



MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	5.483	18.396	1480	%
Magnitude Err	2.825	13.604	1480	%
Phase Error	3.29	-18.65	224	deg
CarrierFreq Err	2.26			Hz
Ampt Droop	-0.02			dB
Origin Offset	-57.39			dB
Gain Imbalance	0.02			dB
Quadrature Err	-0.15			deg
RHO	0.996994			
Mean Power	-33.57	-27.64	2816	dBm
SNR (MER)	25.22			dB

SYMBOL TABLE (Hexadecimal)	
00000	2 C 3 3 C 3 7 4 9 6 7 C F D D 8 0 E
00018	3 2 C 7 B 6 2 4 1 0 C 6 B 2 E 6 A 2
00036	A A 8 9 8 C 4 A 3 A E 4 B 3 E 2 6 0
00054	1 8 E 5 B 7 2 0 D 2 7 4 D E D D C 8
00072	4 2 1 9 E 1 7 5 9 2 B E 4 F B 4 3 5
00090	5 8 2 F 2 6 4 9 2 F 6 E E 8 1 A F 4
00108	F F C 9 4 6 D B 5 3 1 9 A 9 D 4 A 7
00126	2 4 5 8 6 7 8 7 7 C B 5 7 9 3 B A 8
00144	D 0 6 5 9 6 3 4 5 C E D 9 4 2 5 1 4
00162	0 4 0 0 8 A 9 9 C 0 6 1 1 C 2 7 0 5
00180	4 C E 9 1 E 3 6 4 D A 5 7 D B 1 B B
00198	8 9 C 4 E B 0 F 7 E A 4 3 1 D 2 3 C
00216	7 F E 8 5 2 5 5 C A 5 3 5 1 0 8 E 1

Date: 12.OCT.2005 16:36:17

Figure 10 Constellation diagram of option 2 for QAM16 modulation, with a symbol rate of 25 Msym/s.

3.4 Discussion

Although the two design options that are proposed differ slightly, the measurements do not indicate a significant (dis)advantage of each option. More extensive measurements, e.g. including the wireless channel may lead to more insight in the pros and cons of the two design options.

In option 1 the low frequency signal can also be generated in the digital domain (e.g. using a Direct Digital Frequency Synthesiser (DDFS)) and added to the DL data. DDFS brings several advantages like fast frequency switching, high frequency resolution, continuous-phase switching operation, and low phase noise. With DDFS no external VCOs are required and it eliminates the need for data converters that are traditionally used to communicate digital control signals to the VCO. In case of integration it is also desirable to avoid use of multiple VCOs on the same chip, which may lead to parasitic coupling.

4 CONCLUDING REMARKS

In this study a cost effective full duplex FWA feeder system has been developed and tested successfully. The FWA feeder has several cost related advantages: only low frequency RF processing devices are used; RAP installation is easy and maintenance costs are low which is important because of the large number of required RAPs, since cell sizes will be small at the employed high frequencies.

The system was designed in accordance with the IEEE 802.16 requirements. In order to evaluate the FWA feeder design the study objectives are reconsidered. The following objectives were set in the MUSE project:

1) Provide options for centralization of FWA head-end processing functions.
2) Establish feasibility of techniques for carrying microwave signals.
3) Protocol considerations
4) High level component & Network designs

The first objective has been met, since two different options have been developed and tested.

The OFM technique has been shown very suitable to carry microwave signals over fibre. At 17.2 GHz good results have been obtained. This shows that the second objective has been met also. Transparent transport over fibre lengths up to 25 km was demonstrated with data rates of 100 Mbit/s per channel.

Protocol considerations, the third objective, were limited due to the fact that no scheduling algorithm was available for the IEEE 802.16 standard. More study is required here, in particular when wireless measurements are performed and a duplexing scheme is required. However, a relation was established between the QoS requirements in the MUSE project and the definitions in the IEEE 802.16 standard.

Finally, high level component and network designs were performed for a point-to-point configuration. Both standalone tests and joint trial tests, which are to be published in another deliverable, show the robustness and interoperability of the FWA feeder system.

Next possible steps in the further development of the FWA feeder system are:

- Wireless measurements
- MAC protocol design taking into account the extra fibre link latency
- Development of point-to-multipoint configuration FWA feeder system
- System integration
- Development/purchase of signal processing unit for MAC and PHY processing
- Development of an interface to higher layers

These steps will make the system to evolve further so that actual service delivery becomes feasible.

REFERENCES

[1] IEEE Standard for Local and Metropolitan Area Networks, “Part 16: Air Interface for Fixed Broadband Wireless Access Systems.” IEEE 2002.

[2] T. Koonen, A. Ng’oma, H. P. A. vd. Boom, I. Tafur Monroy, P. F. M. Smulders, and G. D. Khoe, “Carrying microwave signals in a GIPOF-based wireless LAN”, in Proceedings of the Plastic Optical Fibres Conference, 2001, pp 217 - 223.

[3] T. Koonen, A. Ng’oma, P. F. M. Smulders, H. P. A. vd. Boom, I. Tafur Monroy, and G. D. Khoe, “In-House networks using Multimode Polymer Optical Fiber for broadband wireless services”, Photonic Network Communications, Vol. 5, No. 2, 177-187, (Kluwer, 2003).

[4] A.M.J. Koonen, A. Ng’oma, M. Garcia Larrode, F.M. Huijskens, I. Tafur Monroy and G.D. Khoe, “Novel Cost-efficient Techniques for Microwave Signal Delivery in Fibre-Wireless Networks”, ECOC 2004, 2004.

[5] A. Ng’oma, “Radio-over-Fibre Technology for Broadband Wireless Communication Systems,” PhD Thesis, Dept. Telecommunication and Electronic Engineering, Eindhoven Univ. of Technology, Eindhoven, The Netherlands, 2005.

[6] http://www.atmel.com/dyn/resources/prod_documents/doc5431S.pdf

[7] http://icwww.epfl.ch/publications/documents/IC_TECH_REPORT_2004100.pdf

[8] http://www.commsdesign.com/design_corner/showArticle.jhtml?articleID=59200057

[9] http://www.iele.polsl.gliwice.pl/~izi/DSPtech.pdf

[10] MUSE deliverable WPC1_0005_V07_WPC1.1.1.3 End-to-End QoS solution for Public Ethernet

[11] H.B. Kim, H. Woesner, and A. Wolisz, "A Medium Access Control Protocol for Radio over Fiber Wireless LAN Operating in the 60-GHz Band", In Proc. of 5th European Personal Mobile Communications Conference (EPMCC), Glasgow, Scotland, April 2003

[12] Garcia Larrode, M.; Koonen, A.M.J.; Vegas Olmos, J.J.; Rijckenberg, G.-J.; Dang Bao, L.; Niemegeers, I.: Transparent transport of wireless communication signals in Radio-over-Fibre systems proc. NOC 2005, 5-7 July 2005, London, UK, 2005, pp. 83-90. ECO [06.11]