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Date Submitted	01-14-2001
Source	Yonatan Manor Oren Semiconductor P.O.Box 201 Yoqne'am Illit, 20692, Israel Tel: 972-4-9095501 Fax: 972-4-9894566 E-mail: yonatan@oren.co.il
	Howard Sandler and Chris Tappenden, Nortel Networks Email: ctappend@nortelnetworks.com Tel: 408-863-2300 Chet Shirali and Menashe Shahar, Vyyo Email: cshirali@vyyo.com John Sanford, Remec Email: jsanford@remec.com Sanjay Moghe, RF Solutions Randy Howell, Unique Broadband Systems randyh@uniquesys.com
	George Fishel Communications Consulting Services 10 Bretz Circle Shermans Dale PA 17090 Phone: 717-582-2507 Fax: 717-582-3637 Cell: 717-580-7838 Email: grfishel@pa.net
	Baruch Buskila, Amos Dotan WaveIP, P.O.Box 336 Yoqne'am Illit, 20692, Israel Tel: 972-4-993-7333
Re:	Proposal submitted in response to Call for proposal on PHY specifications in IEEE 802.16.3 on 2000-9-15
Abstract	This document presents the outline of the PHY specifications for Broadband Wireless Access in the MMDS band. Orthogonal Frequency Division Multiplexing-based technology is proposed to allow full non-line of sight implementation. Adaptive Modulation is proposed to increase capacity. A data-framing structure is proposed which allows straightforward implementation of Adaptive Modulation and results in over 60% increase in capacity compared with fixed modulation. The forward error correction scheme is concatanated Reed Solomon and convolutional coding with Viterbi decoding..
Purpose	Contribution as a proposal for consideration as the PHY layer specifications for 802.16.3.
Notice	
Release	
Patent Policy and Procedures	

IEEE 802.16 Broadband Wireless Access Working Group

Unified PHY for Communication (MMDS)

Table of content:

1. Overview

The PHY layer in the MMDS system architecture is responsible for signal processing functions including modulation, demodulation, forward error correction etc on both the down stream and upstream data transfers between the base station (head end) and the consumer premise equipment (CPE). The goal of having a standardized system is to have total interoperability between the CPE's and the head end equipment.

There are two basic transmission schemes that have been considered for wireless data transfer: Single Carrier (using QAM modulation) and OFDM (Orthogonal Frequency Division Multiplexing). Several variations of both methods have been proposed.

In general, it is accepted that OFDM results in more robust performance when a clear line of sight is not available between the transmitting and receiving antennas.
In some field trials, OFDM was shown to be more robust in terrestrial reception of digital transmission than QAM based system, and thus can provide better coverage for the MMDS service. The OFDM scheme also is well suited for digital communication where data is delivered in bursts. Data delivery in communication systems, which is combined of concatenated packets of bytes, is naturally matched into the cyclic nature of the OFDM transmission. Demodulation and decoding is better served by OFDM for the multi-user structure of the MMDS system.

However, the OFDM transmission format includes significant redundancy in the form of a guard interval (12% to 25%) and pilot sub-carriers (12% to 26%). This reduces the capacity of the OFDM modulation compared to the Single Carrier QAM based system.

In a typical MMDS deployment, customers having a clear line of sight to the transmitting antenna may be able to get higher connect speeds than those out of the line of sight. However, with a fixed modulation scheme, the system must be set up for the worst-case scenario. Adaptive modulation and adaptive FEC are ways to provide better coverage for distant CPEs while enhancing data delivery rate to nearby CPEs. Using Adaptive Modulation, data throughput can be improved significantly (60% by the calculation discussed in this proposal) by using higher order modulation (up to QAM 64) for subscribers with better signal to noise and lower order modulation (QPSK) for subscribers with inferior signal to noise.

The data framing structure proposed here allows relatively straightforward way of implementing adaptive modulation in a symmetrical fashion. Data framing is designed to integrate with the block nature of the OFDM symbol. The data is divided to Frames and super frames(Sframe). A Frame is made of all sub-carriers in one OFDM symbol. A Sframe is made of a whole number of Frames. A Sframe is the basic cell of adaptive modulation and adaptive FEC. Each Sframe is divided to QAM4, QAM16 and QAM64 segments, each with different FEC protection. A headed, modulated at QAM4 with most powerful FEC is included at the beginning of each Sframe. The headed content includes the length, modulation and FEC parameters of the data segments within the Sframe.

A communication based on OFDM modulation can be easily integrated into the existing MAC layer protocol and hardware implementations. Data delivery interface is compatible to the existing MAC based on the DOCSIS standard.

The OFDM system proposed here is called Enhanced OFDM (EOFDM) and includes all the benefits of OFDM in non-line of sight channels with the added benefits of real-time packet-by-packet adaptive modulation and adaptive forward error correction.
The chapter below describes the EOFDM based communication system.

The FEC in the down and up stream is based on the DVB-T with little modifications. To support the adaptive modulation and the burst nature of the modulation, the byte interleaving is eliminated and the energy dispersal is moved after the RS encoding. Two options for the bit interleaving are proposed for long and short FFT blocks. In the EOFDM the pilot position and density have been increased compare to the DVB-T to provided one sub-carrier structure that supports the continuous modulation of the down stream and the burst nature of the upstream link.

Interface to the MAC is kept general to support existing MAC definitions. The MPEG2ts convergence layer is not used to save the 4 bytes header. The structure of packing the MAC frames is kept opened for discussion. It can follow the structure of data content followed by the pointer field in every RS code word in any single data segment. Since the data segment are short and may include a single or few MAC frames it may be more efficient just to pack continuous MAC frames without the pointer field separation.

2. Down stream

2.1. General

This section describes the downstream transmission. The down stream transmission is a continuous stream of OFDM symbols.

2.2. Frame Adaptation

2.2.1. Adaptive modulation and FEC

In this mode burst of data bytes are modulated into bursts of OFDM sub-carriers and OFDM symbols. The modulated bursts are concatenated into a continuous transmission. Groups of OFDM sub-carriers are assigned to each CPE and modulated according to the reception quality of the CPE. Any CPE must be able to decode only the sub-carriers and symbols that are destined to it.

The WMTS organizes the data for transmission according to the channel quality of the targeted CPEs. The data for transmission is divided to blocks, called Sframe. Each Sframe starts with a QAM4 header and can have up to 6 additional segments.

At start up, the demodulator locks on the OFDM cyclic block. It then detects the cyclic pattern of the sync pattern and identifies the framing structure of the transmission. Only then decoding of the dynamically modulated signal is started.

The WMTS will set the modulation level for each CPE according to the C/n reported back to the WMTS, using the Sframe header. The CPEs that can receive a strong signal (>23 dB C/n) will receive and decode data using QAM64 modulation with minimal FEC. Other CPEs with moderate reception (>10dB C/n) will receive only QAM16 with appropriate FEC. At a reception level of below10dB C/n only QAM4 modulation can be used. Control parameters that must be delivered to all CPEs will be modulated by QAM4.

The FEC processing includes: RS encoding, randomization, convolutional encoding with flexible puncture rate and bit interleaving. There is no Byte interleaving.

With EOFDM modulation all the CPEs will be able to synchronize on the concatenated symbol stream, thus remain locked to the station even if the signal quality does not support data delivery.

2.2.2. Sframe Structure

The Sframe and the Frames are always cyclic. Each Sframe is made of a whole number of Frames. A Frame is defined as data in an OFDM block. The start of any Frame includes 6 QPSK symbol sync pattern. The pattern has two polarities. A positive polarity indicates the start of a Sframe. A negative polarity indicates the start of a Frame.

The Sframe is thus constructed of:

1) QAM4 header. The header describes the parameters of the 6 segments to follow in the next Sframe.
2) Termination of last Sframe segment. This is done to prevent data packet splitting because of Sframe termination. The modulation parameters of this segment are the same as of the last segment of the previous Sframe.
3) TBD number of data segments; each is assigned with a length and a burst profile – representing modulation and FEC parameters.

In EOFDM the order of the data segments is free and includes the following components.

1. QAM4 segment. In this segment data to all QAM4 customer CPEs is delivered.
2. QAM16 segment. In this segment data to all QAM16 customer CPEs is delivered.
3. QAM64 segment. In this segment data to all QAM64 customer CPEs is delivered.

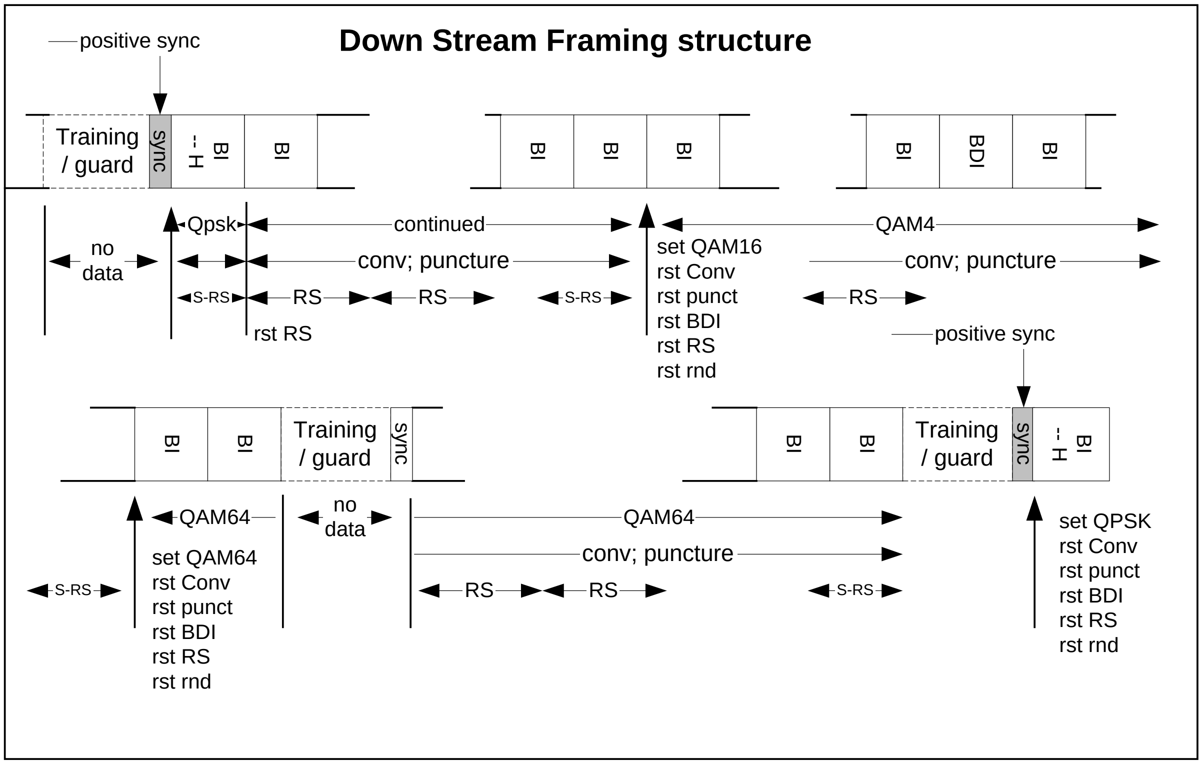
If there is no data to be delivered in any given Sframe, the WMTS encode data to fill the remaining BI blocks with randomly generated symbols. The CPE will try to decode it but inform a RS decoding failure. The MAC ignores this data using the length of the data packet to terminate meaningful data.

Each data segment in a Sframe is made of a whole number BI blocks that are processed by the bit interleaver (BI) and the bit deinterleaver (BDI) at the receiver. The length of each segment is thus reported in the header in units of BI blocks.The BI block has a programmable length with default of 60 symbols long.

Each data segment constitutes a single transmission burst, excluding the termination segment. The FEC of each segment must be initiated and terminated independently of other data segments. Each data segment is composed from a whole number of RS code words, excluding the last code word that may be shortened. Convolutional encoding is employed on the randomized output of the RS encoder. The last RS code word in any data segment is padded with null data to reach the end of the last BI block, leaving 6 symbols to terminate the convolutional encoder. At the start of each data segment the BI, RS, randomizer and convolutional encoding is restarted.

Each data segment can have a length of zero symbols. Each data segment can cover the whole length of the Sframe. The last data segment can continue into the next Sframe, where the next Sframe header indicates the continuation. Each segment is divided into BI blocks and protected by: randomization → RS encoding → conv. encoding.

The packet arrangement is shown in the diagram below.



2.2.3. Sync pattern

The sync pattern is inserted at the start of each OFDM block. The Sync pattern is a fix pattern with 5 symbols long. The pattern has two polarities.

Positive polarity = Sync[0:4]

Negative polarity = -Sync[0:4]

A positive Sync indicates the start of a Sframe. A negative Sync indicates a normal Frame. The Sync is used to identify the duty cycle of the Sframe by the CPE.

Note: different pilot configuration may require modification of the number of Sync sub-carriers.

2.2.4. Low rate system bits

In some pilot configurations there are unassigned sub-carriers remaining. These sub-carriers can be used for low rate data bits transfer. These sub-carriers are modulated by BPSK and are not processed by the FEC decoder. These bits can be programmed for any system application, such as system pre-setting parameters. These to sub-carriers are appended to the Sync pattern before SI operation..

2.2.5. Header

The header is placed at the start of every Sframe. The header indicates the structure of the data segments in a Sframe. The header always contains the structure of the next Sframe to follow.

The header is always modulated by QPSK, using1/2 rate convolutional encoding. The last 6 symbols of the header BI blocks are use to terminate the convolutional encoder.

The header size depends on the BI block size. For BI of 60 symbols the header is made of 2 BI block. Discounting the 6 termination symbols the 114 remaining symbols constitute 14 bytes of RS code word with 6 redundancy bytes, RS(14,6).

The header contains the following encoded information:

1. [length – 7 bits; profile mode - 3 bits] – for continuing from last Sframe
2. [length – 7 bits; profile - 3 bits] – for 1st data segment
3. [length – 7 bits; profile - 3 bits] – for 2nd data segment
4. [length – 7 bits; profile - 3 bits] – for 3rd data segment
5. [length – 7 bits; profile - 3 bits] – for 4th data segment
6. [length – 7 bits; profile - 3 bits] – for 5th data segment – for fragmented last data segment.
7. Header control bits: [cont[1], frag[1]] – cont =first data segment continued; frag=fragmented last data segment that is not with zero length.
8. Reserved bits: 2 bits for BI=60
9. 6 bytes parity bytes for RS (t=3)

The header is treated as an independent segment transmitted on at the beginning of the Sframe. It thus requires FEC termination. The header is always encoded in QPSK with ½ rate coding.

Length – describes the number of BI block allocated for the data segment

Profile – assigns the modulation and puncture rate for the data segment.

The following profiles is pre-set by the MAC and can support gradual selection of modulation and puncture rate vs. reception signal quality:

Profile	0	1	2	3	4	5	6	7
C/n dB	3 - 6	6 - 9	9-12.5	12.5-16.5	16.5 -19	19-23	23-up	
Modulation	QPSK p=½	QPSK p=3/4	QAM16 p=½	QAM16 p=3/4	QAM64 p=2/3	QAM64 p=5/6	QAM64 no conv.	reserved

2.2.6. Data segment

A data segment is a continuous stream sub-carriers in OFDM that are modulated in one modulation level and using a common puncture rate. The data segment can include few concatenated data packets. A data segment can span over 2 Sframes. If a longer transmission is required the previous data segment must be terminated and a new data segment must be restarted with the continuing data. The length and the FEC parameters are defined in the header for each data segment.

There are up to 8 pre-configured profiles that are designed to provide gradual FEC protection for various reception conditions. Each profile specifies one of the modulation levels (QAM4-16-64) and one of the puncture rates for the convolution encoder (1/2, 2/3, ¾, 5/6, 7/8, no convolution). The header profile is a default profile with fixed parameters (QPSK, rate ½, RS TBD). The other 7 profiles are defined in the MAC DCD message. Profile 0 will serve the header and the DCD messaging.

A segment is always consisting of integral number of BI blocks. If necessary, stuff bytes of 0xFF are appended to the end of last MAC frame till the end of BI. If there is no data to fill the entire super frame, then full BI blocks of 0xFF are added till the end of super frame. These empty BI blocks are appended to the end of the last data segment.

A start of any data segment, except of the termination segment, indicates to the MAC layer a start of MAC frame. Starting at these points, the MAC layer should follow the MAC frames, using the length in the MAC header, to identify the MAC frame boundaries within a data segment.

The FEC in each segment includes:

1) RS codes RS(N,t) programmable

2) Stuff bits

3) Randomizer

4) Convolutional code (K=7) with puncture:1/2, 2/3, ¾, , 7/8.

5) BI – programmable length block interleaver of symbols proposed lengthThe BI length must be a multiply of 6.

6) QAM gray coding

FEC of each data segment is initiated separately, excluding a termination data segment: The following initializations are set at the start of a data segment:

1) A new RS code word.
2) Reset the randomizer.
3) Initialize the convolutional encoder
4) Start of BI and BDI blocks.

In the termination data segment only the BI are initialized.

At the end all data segments the following process are done:

1) Fill RS code words of 0xFF to the end of a BI block.
2) Implement a shortened RS block to the end of a data segment.
3) Terminate the convolutional encoder with last 6 zeros, and complement with random bits to the end of the last 6 symbols symbols. (only in QMPSK ½ rate the last 6 zeros occupy the last 6 symbols.

The decoding of the header is treated as a data segment that includes 2 BIs and shortened RS (14,6). To avoid breaking of decoding the termination data segment, the decoding of the header can be delayed to the interval between other data segments.

2.2.7. FEC termination of a data segment

1) Any segment includes a whole number of BI blocks of symbols (or sub-carriers). A segment, therefore, always terminates at the end of a BI block.
2) Null bytes are added to the last RS code word at the end of the BI block, leaving 6 bits for convolutional code termination. The added bytes in the last RS codeword are filled with null ‘0xFF’s.(PHY operation). The padding with null bytes ensures that the remaining decoded bits is greater or equal than 6 but less than 14.
3) Empty BIs will be filled by 0xFFs.
4) Convolutional termination starts 6 symbols before the end of the BI block, at the first X output of the convolutional encoder. Termination is done by 6 zeros added to the encoder at the end of the data Bits.
5) Post-termination bits are added directly to the mapper to complete the symbols of the last BI. Those bits are not decoded by the Viterbi decoder.
6) If the remaining number of bytes to the end of the BI is greater than 6, then shortened last RS codeword is applied (encoding and decoding); else fill bytes are added to the end of the next BI, and in the decoding all last bytes are discarded.

2.2.8. FEC termination of the header:

1) Header is 2 BIs.

2) Convolutional termination is done by 6 zeros added to the encoder at the end of the data Bits.

3) RS codeword is fixed to shortened RS(14,6).

2.2.9. Modulation level

Packet data will be modulated in one of three levels:

1. QPSK
2. QAM16
3. QAM64

To preserve a continuous energy of transmission the RMS of all the modulation levels is kept equal such that

$$E[C^*C']_{QPSK} = E[C^*C']_{QAM16} = E[C^*C']_{QAM64}$$

Where C is the complex symbol value.

With 1% allowed tolerance.

An example of implementation in 9 bits precision:

QPSK = [-1 1] * 129

QAM16 = [-3 –1 1 3] * 58

QAM64 = [-7 –5 –3 –1 1 3 5 7] * 28

2.2.10. Data Output Format

Data output after FEC decoding and de-randomization is in the form of continuous bytes concatenated from block of RS code words. The stream of code words may not have a fixed length and may change during data delivery. Data output will be accompanied with the following flags:

1) SOP – this flag signal the start of an RS code word (MPEG2TS flag)
2) SDS – start of a delivering data segment bytes (new flag)
3) RS_fail - A decoding fail indication of the current RS code word (MPEG2TS flag)
4) D_valid – a strobe indicates a valid data at the current output clock (MPEG2TS flag)

Data out can be selected by the CPE to be one of the cases:

1) QPSK only (MAC and data)
2) QPSK and QAM16 or QAM64 (MAC and relevant data)
3) All (MAC and all data)

This should be done to reduce data processing by CPE for which the data segment is not intended for.

2.2.11. Time Stamp

Time information from the WMTS to the CPE is synchronized by the time stamp message. The time stamp message reports the time of the Sframe event in the N next Sframe. In this way the content of the time stamp message is disconnected from the actual time of delivery of the message itself.

The process starts with the timing clock being sampled at any given Sframe event. The time stamp is then calculated by adding $N*DT_{Sframe}$ to the samples clock. Where N is the Sframe packing latency and DT_{Sframe} is the time duration of one Sframe. The time stamp message must be delivered at any time within the current Sfame data.

2.3. OFDM modulation

The EOFDM modulator can operate in two modes. Byte interleaving for all CPEs provides compatibility to the existing standards for data delivery. Adaptive modulation can provide higher delivery rate with additional link layer for organizing the data segments.

The WMTS transmits continuously a sequence of OFDM symbols. The symbols may contain data when available or may just deliver redundant information to keep a continuous signal.

2.3.1. Adaptive modulation

When adaptive modulation is applied only static scattered pilots are used, while modulation may be changed throughout the EOFDM symbol. The data carrying sub-carriers may be modulated in each symbol, and within each symbol in different form, in one of the following: DQPSK, QPSK, QAM16 or QAM64.

Each CPE unit can lock on the timing and carrier frequency of the transmitted signal and subsequently continuously equalizes the channel, regardless of the modulation format. Modulation format of data to each CPE will be assigned according to the reception quality at its location.

The transmitted signal is organized of data packets that are processed into a symbol stream and then each preceded by the Sync signal. The concatenated packets are parsed into blocks in the length of the usable data carrying sub-carriers in each OFDM symbol.

The allocation of modulation format in a continuous OFDM symbol stream before SI is illustrated below.

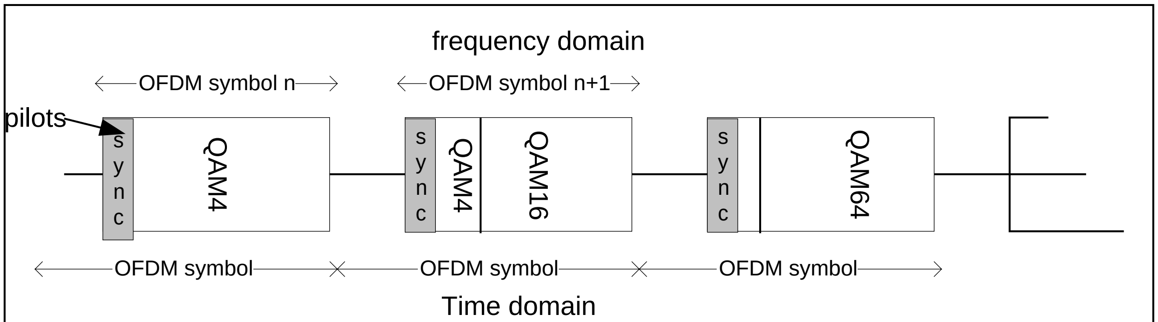


Illustration: OFDM symbol concatenation

The symbol interleaving (SI) technique is applied to obtain frequency diversity. Data carrying sub-carriers are interleaved after concatenating with the sync and before the pilot insertion. The data carrying sub-carriers with different modulation level are not visually separated after the SI in the transmission, but the pilots are still placed in the fix positions. This is demonstrated in the figure below.

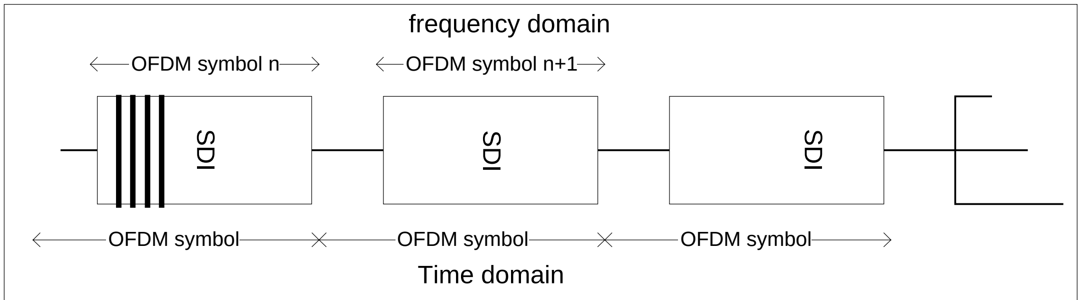


Illustration: OFDM symbol concatenation with SDI

Note: the concatenated pilots are presented in the above figure only at the beginning of the first OFDM symbol.

OFDM symbol is then constructed from the data carrying sub-carriers padded with a fixed pattern of pilots and padded at both side to the length of the FFT operation with zeros.

An IFFT operation is done on each OFDM symbol and the desired guard interval is added. The resulting signal is a continuous concatenated time domain OFDM symbols modulated at base band and preceded with their guard.

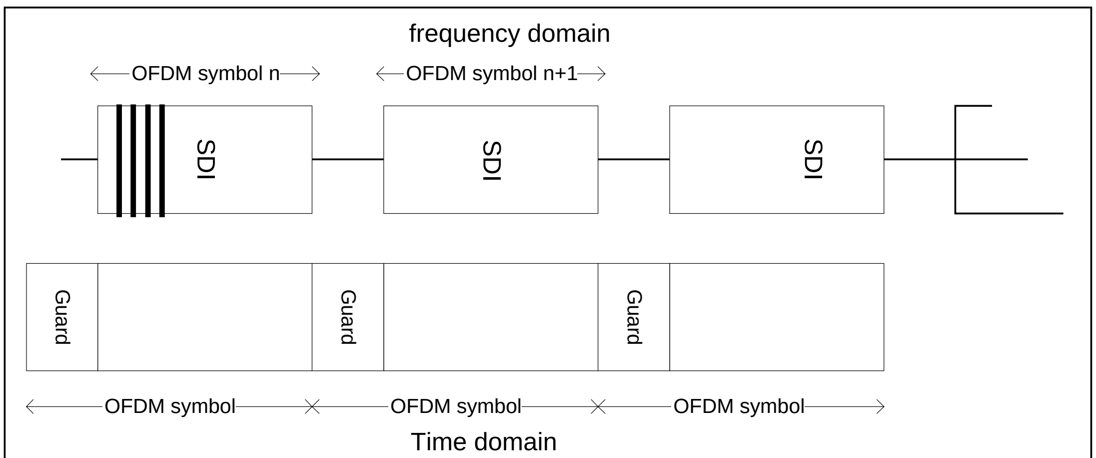
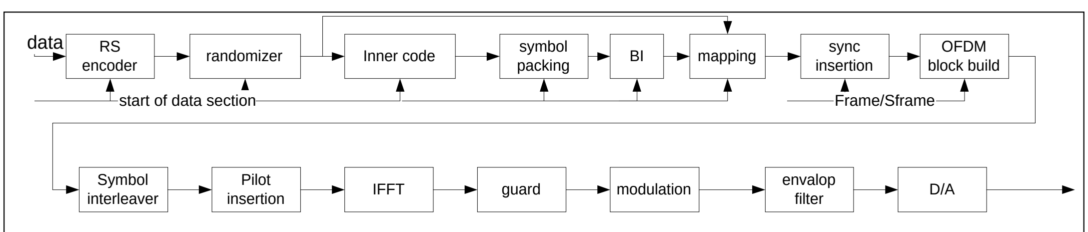


Illustration: Base band OFDM symbol stream

The complete process of encoding and modulation of the EOFDM signal is presented in the diagram below.



Adaptive OFDM - down stream

2.3.2. Synchronization

All the CPE receivers lock on the continuous OFDM symbol stream. While locking they provide information about carrier offset, timing of OFDM symbol start and gain of the received signal. The receivers can also calculate the channel fading pattern.

The following are the parameters of reception quality that can be calculated by the CPE.

Carrier offset – carrier offset includes all the down conversion stages in the signal transmission and reception without the ability to separate the source of offset error. Carrier frequency precision is required in single Hz precision.

Timing – timing of the OFDM symbol start is recorded. Precision depends on signal level. Expected precision: TBD of the clock timing.

Gain – Gain signal amplification by the receiver. Expected precision: <3dB.

Channel model – channel model in time or frequency domain.

2.4. MAC interface

The MAC should provide interface to the encoder to manage the data encoding and the Sync insertion.

Serial data input to WMTS encoder - this is a stream of data made of MAC frames structure. Each MAC frame is attached with a burst profile that indicates the highest modulation level to be used and FEC setting. The data stream is packed into data segments and concatenated with the header content. From this information the encoder generates the symbols stream. The header is always informs the data segments parameters for the next Sframe.

2.5. Data encoder

The following are items that are applied to all modes.

2.5.1. Data segment control (DSC)

Data input to the data segment controller are PDUs of data. Each PDU is assigned by the MAC with the required burst profile for transmission. The DSC packs the DPUs data into data segment according to a TDB algorithm, calculates the header in each Sframe and constructs the Sframe and OFDM symbols.

The data segment controller sends data to the RS encoder in a stream of bytes.

2.5.2. RS encoder

Data input from the DSC is a series of code words, containing a preassigned length of data bytes per code word (N). The last byte in a data segment can be a shortened RS code word where the zeros are not transmitted.

The header is also constructed from a shortened RS code word with a fixed parameters (N=14,t=3).

The RS encoder must be able to provide the following selections: RS codes over GF(256) with T=1 to 10 or with no FEC.

The following RS generator polynomial is supported:

$g(x) = (x + \alpha^0)(x + \alpha^1)\ldots(x + \alpha^{2T-1})$, where the primitive element is 0x02

The following RS primitive polynomial is supported:

$p(x) = x^8 + x^4 + x^3 + x^2 + 1$

The maximum allowed code word is 255, data plus parity byte.

The number of redundancy bytes, 2T, of the last shortened code word is set according to the length of the RS code word. This provides an even BER performance for any code word length.

The following table of T vs. N will be used for BER $=10^{-8}$

N	7 - 15	16 - 31	32 – 63	64 – 95	96 - 143	144 - 204
T	3	4	5	6	7	8

The shortest RS code word is thus N=7.

2.5.3. Randomizer

The randomizer operates on the output of the RS encoder. All the data in the packet shall be randomized in accordance with the configuration below.

The polynomial for the pseudo random binary sequence (PRBS) generator shall be:

$$1+x^{14}+x^{15}$$

Loading of the sequence "100101010000000" into the PRBS registers, shall be initiated at the start of a data segment and the header.

2.5.4. Inner coding

The system shall allow for a range of punctured convolutional codes, based on a mother convolutional code of rate ½ with 64 states. This will allow selection of the most appropriate level of error correction for a given service or data rate. The generator polynomial of the mother code are $G_1=171_{OCT}$ for X output and $G2=133_{OCT}$ for Y output.

The mother code of rate ½ shall allow punctured rates of 2/3, ¾, 5/6, and 7/8.

The punctured convolutional code shall be used as given in table 3 below. In this table X and Y refer to two outputs of the convolutional encoder.

Table 3: Puncturing pattern and transmitted sequence after parallel-to-serial conversion for the possible code rates

Code Rates r	Puncturing pattern	Transmitted sequence (after parallel-to—serial conversion)
½	X: 1 Y:1	X_1 Y_1
2/3	X: 1 0 Y:1 1	X_1 Y_1 Y_2
¾	X: 1 0 1 Y:1 1 0	X_1 Y_1 Y_2 X_3
5/6	X: 1 0 1 0 1 Y:1 1 0 1 0	X_1 Y_1 Y_2 X_3 Y_4 X_5
7/8	X: 1 0 0 0 1 0 1 Y:1 1 1 1 0 1 0	X_1 Y_1 Y_2 Y_3 Y_4 X_5 Y_6 X_7

X_1 is sent first

Encoder termination is done by feeding 6 zero bits to the convolutional encoder at the end of the data in each data segment.

2.5.5. Symbol packing and inner interleaving

Symbol packing is done is combined with an optional bit interleaving operation. Bit interleaving is a block operation intended to disperse bits errors at the input to the Trellis decoder.

The interleaving operation can be bypassed by setting the interleaver pointer to the singular case:

$H_{0..v}(w)=\ 1$ for all mapped levels

2.5.5.1. Symbol packing

The input is demultiplexed into v sub-streams, where v=2 for QPSK, v=4 for 16-QAM, and v=6 for 64-QAM.

The demultiplexing is defined as mapping of the input bit, x_{di} onto the output bits $b_{e,do}$.

$$X_{di} = b_{[di(mod)v](div)(v/2)+2[di(mod)(v/2)],di(div)v}$$

Where: x_{di} is the input to the demultiplexer;

di is the input bit number ;

$b_{e,do}$ is the output from the demultiplexer ;

e is the demultiplexer bit stream number ($o \leq e < v$) ;

do is the bit number of a given stream at the output of the demultiplexer ;

mod is the integer modulo operator ;

div is the integer division operator;

The demultiplexer results in the following mapping:

OSPK: x_0 maps to $b_{0,0}$

x_1 maps to $b_{1,1}$

16-QAM transmission:

x_0 maps to $b_{0,0}$

x_1 maps to $b_{2,0}$

x_2 maps to $b_{1,0}$

x_3 maps to $b_{3,0}$

64-QAM transmission:

x_0 maps to $b_{0,0}$

x_1 maps to $b_{2,0}$

x_2 maps to $b_{4,0}$

x_3 maps to $b_{1,0}$

x_4 maps to $b_{3,0}$

x_5 maps to $b_{5,0}$

2.5.5.2. *Bit interleaving*

Each sub-stream from the demultiplexer is processed by a separate bit interleaver. There are therefore up to six interleavers depending on v, labelled I0 to15 . I0 and I1 are used for QPSK, I0 to I3 for 16-QAM and I0 to I5 for 64-QAM.

The block size is the same for each interleaver, but the interleaving sequence is different in each case. The bit interleaving block size is 60 bits. The block interleaving process is therefore repeated exactly 4 times per segment.

For each bit interleaver, the input bit vector is defined by:

$B(e) = (b_{e,0}, b_{e,1}, b_{e,2}, \ldots, b_{e,LH0-1})$ where e ranges from 0 to v-1

The interleaver output vector $A(e) = (a_{e,0}, a_{e,1}, a_{e,2}, \ldots a_{e,125})$ is defined by:

$a_{e,w} = b_{e,He(w)}$ $w=0,1,2,\ldots,LH0-1$

where $H_e(w)$ permutation function which is different for each interleaver.

$H_e(w)$ is defined as follows for each interleaver:

I0: $H_0(w)=$ w

I1: $H_1(w)=$ (w+LH1) mod LH0

I2: $H_2(w)=$ (w+LH2)mod LH0

I3: $H_3(w)=$ (w+LH3) mod LH0

I4: $H_4(w)=$ (w+LH4) mod LH0

I5: $H_5(w)=$ (w+LH5) mod LH0

Where BIlng, LH1, LH2, LH3, LH4, LH5 are parameters.

The default values are:

For BI =126:

LH0 = 126, LH1=63, LH2=105, LH3=42, LH4=21, LH5=84

For BI =60:

LH0 = 60, LH1=30, LH2=50, LH3=20, LH4=10, LH5=40

The outputs of the v bit interleavers are grouped to from the digital data symbols, such that each symbol of v bits will consist of exactly one bit from each of the v interleavers. Hence, the output from the bit-wise interleaver i a v bit word y' that has the output of 10 as its most significant bit, i.e.

$$y'_w=(a_{a,0},a_{1,w},\ldots a_{v-1,w})$$

In interleaving bypass mode all $H_{1..v}(w)$ are set to one thus disabling the bit interleaving function.

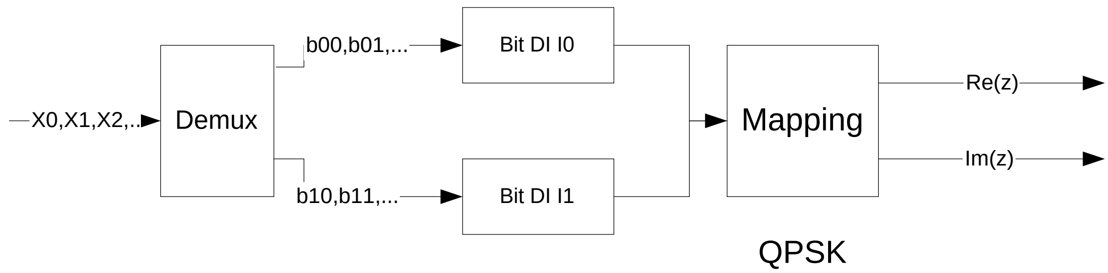


Figure 3a: Bit DI with QPSK

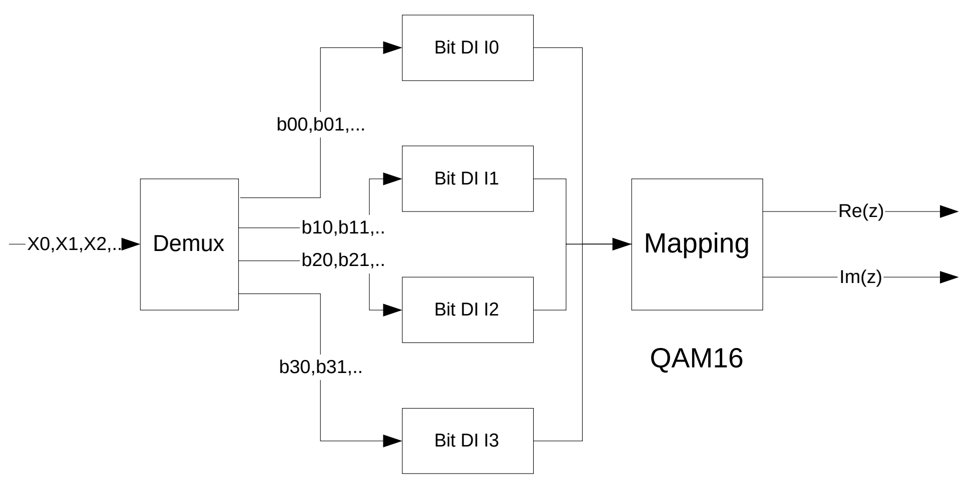


Figure 3b: Bit Di with QAM16

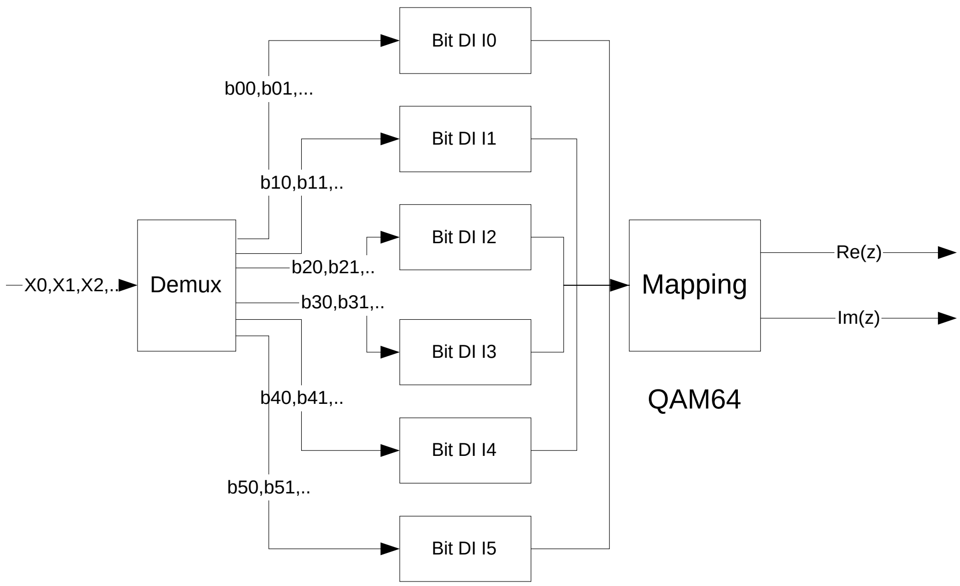


Figure 3c: Bit DI with QAM64

2.5.6. Constellation mapping

All data carrying symbols are using Gray mapping.

Gray mapping is applied according to the following method for QPSK, 16-QAM and 64-QAM. The mapping shall be performed according to figure below.

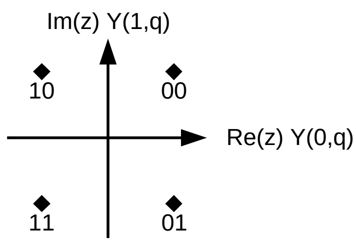
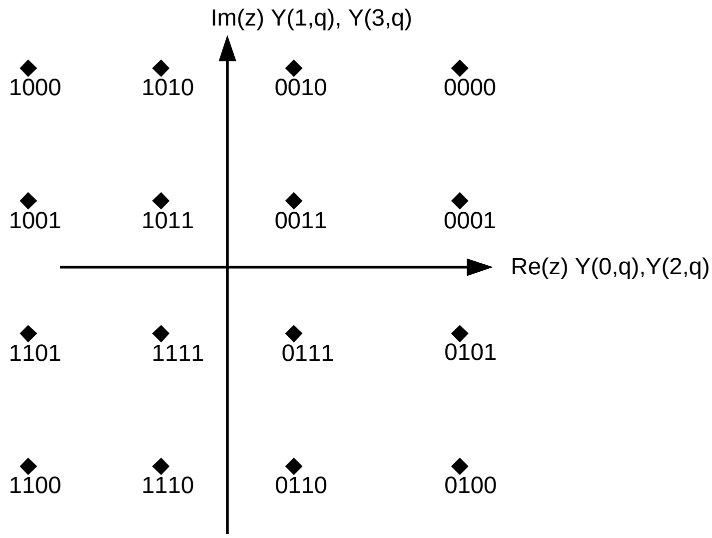


FIgure 4a: QPSK, bit ordering: Y)0q), Y(1,q)



QAM16, bit ordering: Y(0,q), Y(1,q),Y(2,q),Y3,q)

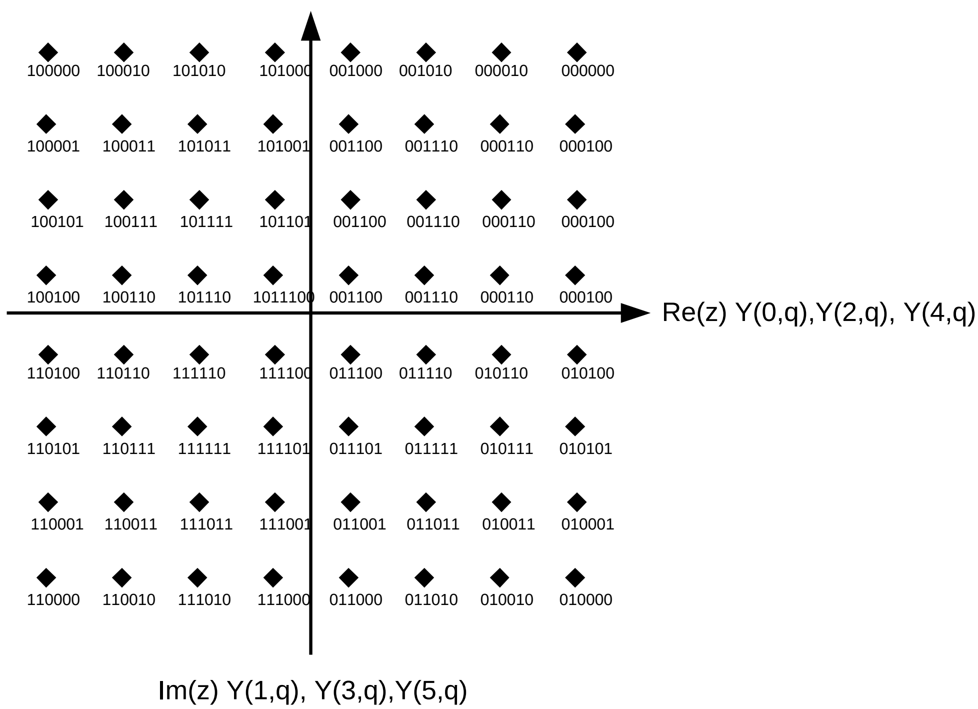


Figure 4c: QAM64, bit ordering: Y(0,q), Y(1,q),Y(2,q),Y3,q),Y(4,q),Y(5,0)

2.6. EOFDM Down stream signal construction

2.6.1. Symbol Interleaver (SI)

Symbol interleaving is done according to the DVB-T. The bit permutation table is extended to support symbols based on FFT length of 256-2K.

The symbol interleaver / de-interleaver acts on blocks of N data words.

The symbol interleaver / de-interleaver input is the vector $Y' = (y'_0, y'_1, y'_2, ... y'_{N-1})$.

The interleaver / de-interleaver output vector $Y = (y_0, y_1, y_2, ... y_{N-1})$ is defined by:

$$y_q = y'_{H(q)}\ , \qquad q = 0,1,2,...N-1 \qquad \text{interleaving}$$

$$y_{H(q)} = y'_q\ , \qquad q = 0,1,2,...N-1 \qquad \text{de-interleaving} \qquad (1)$$

H(q) is a permutation function defined as follows:

1. Prepare a sequence of $M_{\max}$ words R'_i where $i = 0,1,..., M_{\max} - 1$. Each word is a binary N_{reg} bits word. The binary word length is given by $N_{reg} = \lceil \log_2(N) \rceil - 1$ where N is the number of data words in the SI block, and $\lceil\ \rceil$ comes for rounding the element to the nearest integers towards infinity. The sequence length is $M_{\max} = 2^{\lceil \log_2 N \rceil} = 2^{N_{reg}+1}$. The sequence creating process is detailed in the next section.
2. The first two words are the zero words, the third one is 1; i.e.:

   $i = 0,1 \qquad R'_i[N_{reg} - 1, N_{reg} - 2,...,1,0] = 0,0,...,0,0$

   $i = 2 \qquad R'_i[N_{reg} - 1, N_{reg} - 2,...,1,0] = 0,0,...,0,1$

   For $2 < i < M_{\max}$ create R'_i by one place right shifting of R'_{i-1}, i.e.:

   $$R'_i[N_{reg} - 2, N_{reg} - 3,...,1,0] = R'_{i-1}[N_{reg} - 1, N_{reg} - 2,...,2,1]$$

   and adding the left bit according to the formulae given in the following table:

Data block length	N_{reg}	$R'_i[N_{reg} - 1]$
1k<N<2k	10	$R'_i[9] = R'_{i-1}[0] \oplus R'_{i-1}[3]$
512<N<1k	9	$R'_i[8] = R'_{i-1}[0] \oplus R'_{i-1}[4]$
256<N<512	8	$R'_i[7] = R'_{i-1}[0] \oplus R'_{i-1}[2] \oplus R'_{i-1}[3] \oplus R'_{i-1}[4]$
128<N<256	7	$R'_i[6] = R'_{i-1}[0] \oplus R'_{i-1}[3]$
64<N<128	6	$R'_i[5] = R'_{i-1}[0] \oplus R'_{i-1}[1]$
32<N<64	5	$R'_i[4] = R'_{i-1}[0] \oplus R'_{i-1}[2]$

3. The addresses sequence R_i is derived from the sequence R'_i by the bit permutation given by the following table:

R'_i bit positions	9	8	7	6	5	4	3	2	1	0
R_i bits, $N_{reg} = 10$	0	7	5	1	8	2	6	9	3	4
R_i bits, $N_{reg} = 9$		tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
R_i bits, $N_{reg} = 8$			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
R_i bits, $N_{reg} = 7$				tbd	tbd	tbd	tbd	tbd	tbd	tbd

R_i bits, $N_{reg}=6$					tbd	tbd	tbd	tbd	tbd	tbd
R_i bits, $N_{reg}=5$						tbd	tbd	tbd	tbd	tbd

4. The permutation function H(q) is defined by the following algorithm:

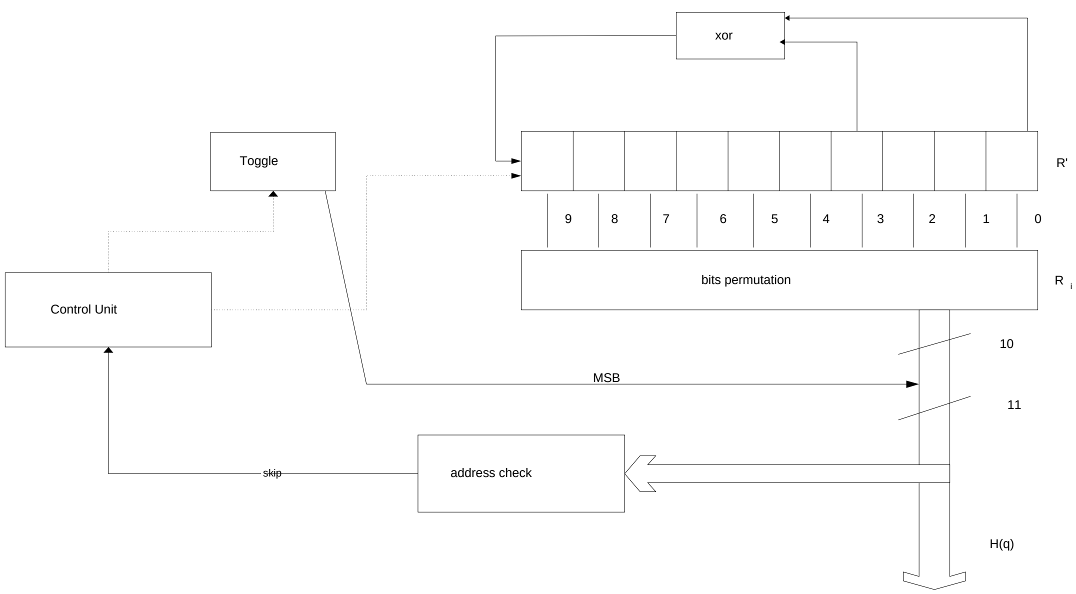
q=0
for (i=0; i< $M_{\max}$; i=i+1)

{ $H(q) = (i \bmod 2)\cdot 2^{N_{reg}} + \sum_{j=0}^{N_{reg}-1} R_i[j]\cdot 2^j$

if (H(q)<N) q=q+1; }

Explain: The sequence R_i created according to paragraphs 2 and 3 has $M_{\max}$ words, but each word appears twice (as R_i has one bit less than needed for $M_{\max}$ different words presentation). Thus, H(q) is made by the addition of one bit to R_i. This bit is added as the msb, and it is 0 or 1 according to the parity of i, the index of the R_i in the sequence. We get $M_{\max}$ integers between 0 and $M_{\max}$-1, which are used as addresses of the data words being interleaved. In case N< $M_{\max}$ the algorithm skips over the addresses larger than N-1, as they are illegal. Figure 1 shows a scheme of the process of preparing H(q).

Figure 1 **: Mechanism for defining H(q) (shown for 2k mode)**



2.6.2. Data carrying sub-carries

For BI = 126

There are 3*126 data carrying sub-carriers in 0.5K mode, 6*126 in 1K mode and 12*126 in the 2K mode.

For BI=60

There are 3*60 data carrying sub-carriers in 0.5K mode, 6*60 data carrying sub-carriers in 0.5K mode, 12*60 in 1K mode and 24*60 in the 2K mode.

.

2.6.3. EOFDM pilots

Pilots are inserted following the SI operation.

Continual pilot are inserted at every 6th sub-carrier. The pilots can be set to interchange position every second Frame, starting in a Sframe, from positions 1,7,13,19.. to position 1,4,10,16,22,….. This provides better equalization of strong multipath.

OFDM symbol construction for BI = 60 table:

FFT	Zeros [left, right]	Fixed pilots position	Scattered pilots (even OFDM sym	Scattered pilots (odd OFDM sym	Data sub-carriers	BI size
2K	155, 155	1, 1738	7:6:1735 289 pilots	4:6:1732 304 pilots	1440 =24*60	60
1K	75, 75	1,874	7:6:871 145 pilots	4:6:868 145 pilots	720 12*60	60
512	35,35	1, 442	7:6:439 73 pilots	4:6:436 73 pilots	360 6*60	60
256	15, 15	1, 226	7:6:223 37 pilots	4:6:220 37 pilots	180 3*60	60

Every OFDM symbol includes in addition 2 symbols for low bit rate system setting and 5 symbols for the sync pattern.

An optional pilot configuration for the downstream for a pilot density of every 12th position is presented in Appendix A.

All pilots are BPSK modulated with zeros in the imaginary components. The pilot amplitude is set such that:

$$\mathrm{Real}(C) = +/- 4/3 \qquad \text{and} \qquad \mathrm{Imag}(C)=0$$

With boosted power of:

$$E[C^*C']_{pilot} = 16/9 * E[C^*C']_{QAM}$$

The pilots are generated by a PRBS sequence to set the polarity of the imaginary component:

PRBS=0 ➔ C_{pilot}

PRBS=1 ➔ $-C_{pilot}$

2.6.3.1. PRBS for Pilots

The PRBS for pilot generator is based on the polynomial:

$$X^{11} + X^{2} + 1.$$

The PRBS is initialized with the strt value of 11111111111, such that the output bit from the PRBS coincides with the first active subcarrier. A new value is generated by the PRBS on every used carrier(wether or not it is a pilot).

2.6.4. Guard Interval

The guard interval is constructed after the IFFT operation by repeating the end of the OFDM symbol before each symbol. The guard interval can have a length that is a power of 2 fraction of the OFDM symbol length. The following length option for the guard interval is allowed: 1/4, 1/8, 1/16/ 1/32.

2.6.5. Initial Ranging Signal

The initial ranging signal is a time domain signal in the length of one OFDM frame. The signal is composed of three parts. This signal is serving to identify the time delay of arrival of the burst and the intensity of the signal. The IR signal is followed by a normal OFDM frame that contains one data segment. The modulation and FEC parameters of that data segment are QPSK and p=1/2, as that of the header.

The length of the IR signal can be one of the following: 256, 512, 1K and 2K. The OFDM frame following it, containing the MAC message is at the same length.

3. Upstream

Upstream modulation is based on one data segment as described for the down stream. In the upstream each data segment contains only one data packet for delivery (in downstream it may include several data packets). The burst includes a header with the modulation format and the burst length, and the data carrying symbols.

3.1. EOFDM

Data to the WMTS is delivered from many CPE units. Timing and frequency de-multiplexing techniques are applied to share the BW of one channel for all the CPEs in service. Time division is the higher level of channel division and it is based on an OFDM symbol allocation for any transmission. Frequency division is a secondary splitting of the channel BW to sub-bands where each CPE transmits the data. When frequency division is employed more than one CPE can transmit at the same time but each CPE delivers information in only a section of the spectrum.

Transmission by the CPE is always synchronized to the received OFDM symbols stream. The CPE will not transmit unless it is synced to the down stream signal. The transmitted OFDM symbol includes a guard section that has the same length as of the down stream.

The use of FDMA requires orthogonality of reception at the WMTS from all CPEs. This can be achieved in various implementation techniques.

The CPE synchronizes the start of the transmitted OFDM symbol such that the symbol arrives back to the WMTS at the same time as of the down stream OFDM symbol, with a tolerance of 0.5 clock.

3.1.1. Symbol Structure

A sequence of one or more OFDM symbols is assigned to a data segment delivery for each CPE transmission. The WMTS assigns the start of transmission in terms of serial number of OFDM symbols and the starting sub-carrier for transmission in units of BI blocks. The allocation is constructed in BI units which are serialized through the sequence of OFDM symbols. A data segment of one CPE can start and end in the middle of an OFDM symbol and another data segment from a second CPE can start at the following sub-carriers. In this way combined TDMA and FDMA access is provided.

Any data pack can be broken into several data segments. These data segments can be delivered in e sequence of OFDM symbols, occupying the whole OFDM symbol BW or part of it. The BW assigned in each OFDM symbol depends on the data segment length in units of BI. A minimum BW of 2BW is required to provide the FEC with a minimum length of data. The demodulator at the WMTS demodulates the full signal BW. It demodulates and decodes each data segment, that may arrives from a different CPE, independently and assembles the data packs from all CPE transmission.

Each CPE inserts the pilots only in the SC allocated to it and places zero in the rest of the spectrum.

The diagram below shows the formation of an EOFDM symbols that is received at the HUB receiver.

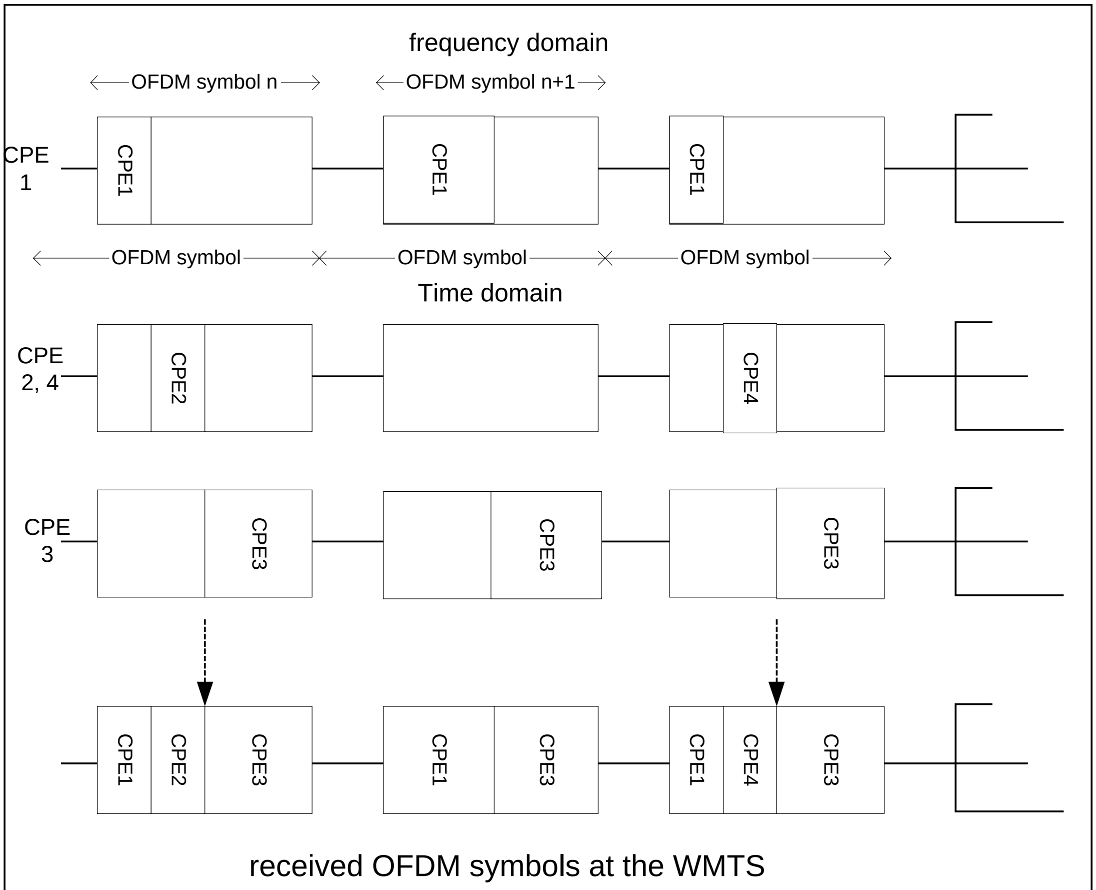


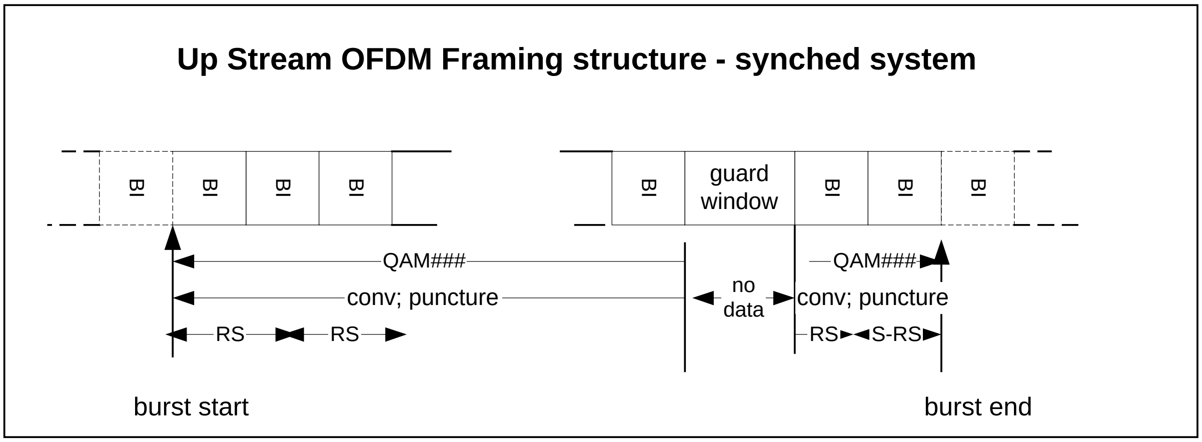
Illustration: upstream OFDM concatanation

Each CPE is allocated to a section of the frequency in any OFDM symbol. The allocation may differ from one OFDM symbol to the next. Any CPE is allowed to transmit only in the pre-allocated continuous sub-band. Any CPE modulates the symbols that are in its allocated band and places zeros in the rest of the band. The CPE inserts the pilots within its allocated sub-band, executes the FFT and transmit the continuous signal in the time domain. The transmission from all CPEs is continuous, although during OFDM symbols that are not in use the energy delivered by that CPE is zero. There will be one BI block separating data segments transmitted in one OFDM symbol.

The protocol for BW BI allocation to any CPE by the MAC is lest opened for MAC consideration.

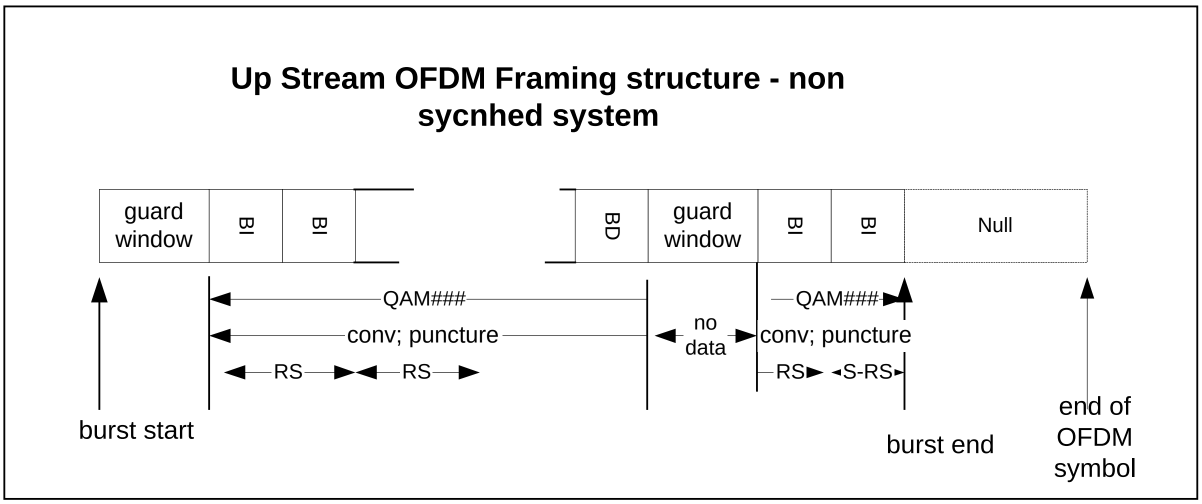
Data segments are not required to terminate at the end of an OFDM symbol and are allowed to continue in the next OFDM symbol.

The diagram below shows a data segment (also a data packet) framing into OFDM symbols.



If the RF system is not synced, thus not providing orthogonallity between CPE's transmission, more than one CPE can not transmit in the same OFDM symbol. In this case any transmission of a data segment starts at the beginning of a new OFDM symbol.

The diagram below shows the data segment framing into OFDM symbols when the RF system is not synced.



3.1.2. Up stream data segment

A data segment is made of one burst of modulated sub-carriers. The data segment FEC is done as in the down stream direction.

A burst is normally made of one data segment only. In some systems it may be desired to define a burst made of two data segments. The first is a header which defines the structure of the second data segment which contains the data. In most systems the information about the burst is known to the HUB and there is no need to deliver the data segment structure.

3.1.3. Request access (RA)

Request access is made of a one data segment. The RA data segment is transmitted in QPSK and p = ½ rate.

The MAC allocates a full (upstream) OFDM slot for RA to all CPEs. Each CPE (CPE's MAC assignment by BI allocation in a burst) randomly selects the required continuous BI blocks (for the RA) in the OFDM symbol to transmit the RA.

The Burst receiver at the HUB calculates the energy of each BI block of the OFDM symbol and tries to decode it.

- Successful decoding approves not contention reception.
- Non successful decoding with high RMS (of pilots) signal indicates contention. The HUB MAC may request power back off from all CPEs.
- Low RMS (of pilots) signal requires no action. The CPEs will try new RA_BI transmission in the next assigned OFDM symbol for RA.

3.1.4. Initial ranging and registration

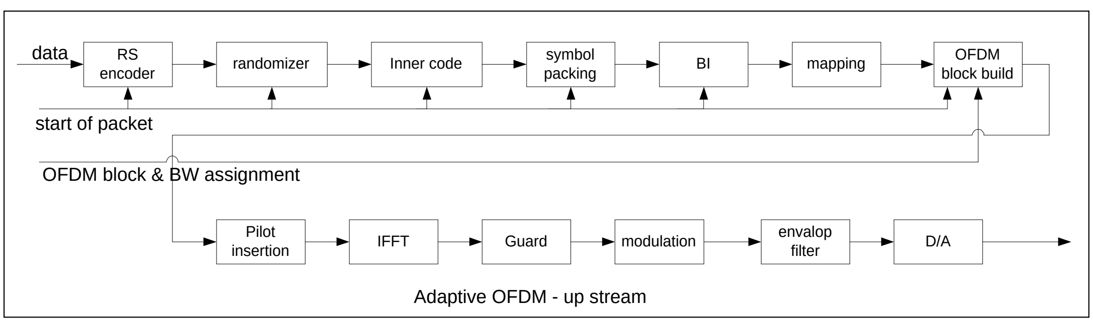
Initial registration and ranging is done by the CPE, transmitting a unique sync signal followed by a second OFDM symbol, in an initial registration contention slot.

The contention slot covers the time window of at least 3 OFDM symbols (including the guard interval). The first 2 windows are for the sync pattern and the OFDM symbol containing the data. The next windows are for the duration of the delayed return signal.

The burst receiver at the WMTS detects the arrival time of the IR burst and if succeeds to decoded the data content in the next OFDM symbol it conveys to the identified CPE the delay time and the signal strength.

3.1.5. Upstream modulation

The diagram below shows the encoding and modulation process.



3.2. *Up stream EOFDM Modulation*

Upstream protocol is using the same FEC building blocks as the down stream.

3.2.1. Active sub-carries

See down-stream allocation.

3.2.2. OFDM pilots

Continual pilot are inserted at every 6^{th} sub-carrier. Pilots are inserted only in the pre-allocated bandwidth. The CPE only insert pilots in the BW allocated to it.

The pilots are generated by a PRBS sequence to set the polarity of the imaginary component:

PRBS=0 ➔ C_{pilot}

PRBS=1 ➔ $-C_{pilot}$

The PRBS is always initiated at the start of the first carrier in an OFDM symbol.

3.3. Up stream encoder

Upstream protocol is using the same FEC building blocks as the down stream.

3.3.1. RS encoder

RS is applied. RS parameters are pre-allocated by the MAC level.

For detail see down-stream.

3.3.2. Randomizer

Is applied in every data segment.

For detail see down-stream.

3.3.3. Symbol packing

For detail see down-stream.

3.3.4. Bit interleaving

Bit interleaving is applied.

For detail see down-stream.

3.3.5. Inner coding

Inner coding is applied in each transmitted packet. Modulation level and puncture rate are pre-allocated by the MAC level.

For detail see down-stream.

3.3.6. Constellation mapping

See down-stream.

3.4. CPE registration

Any CPE that wants to initiate communication must register at the WMTS. Registration is done only after the CPE establishes reception of the down stream signal and detects the time slot for registration. The WMTS assigns time and BW for registration trails. Assignment is in two dimensions: OFDM symbol number and allocated BW of that OFDM symbol.

3.4.1. Synchronization

In EOFDM mode the receiver at the WMTS synchronized to the combined transmission from all CPEs occupying the same OFDM symbol. It will therefore be able to calculate the timing and gain offsets from only the BW allocated for any specific CPE.

In EQAM mode only TDMA is applied and the timing and gains are calculated from the training signal at the beginning of each transmission.

Carrier synchronization is inherently achieved by the structure of the channel down and up RF conversion stages. It is mandatory that all down conversion and up conversion stages will use the same oscillators such that any carrier frequency offset in the up and down channels, due to oscillator offsets, will be the same (up to a fixed factor) with opposite sign. Any CPE that locks on the down-stream signal transmits back in the up-stream direction with the same offset. In that way transmission arriving to the WMTS from all CPEs will be synced to the downstream carrier and also will be synched to each other.

3.4.1.1. Start of OFDM symbol

The CPE must transmit the OFDM symbol such that it arrives to the WMTS at the same timing of the downstream OFDM symbol start. Every CPE receives a correction timing offset from the WMTS to adjust the start of transmission. Synchronization is done in two modes:

1) Initial synchronization – A single CPE transmits a TBD fixed pilot pattern in the pre-allocated OFDM symbol. A complete BW of the OFDM channel is applied for initial synchronization. The WMTS detects the pattern and calculates the timing offset. The WMTS should be able to detect timing offset up to full OFDM symbol length. An ID message is embedded into the OFDM symbol.
2) Continuous tracking – Once within a timing offset of +/- 1 clocks, the WMTS calculates timing correction from the pilots of any CPE transmission in a BW section of the OFDM symbol.

The WMTS reports back to the CPE the required correction.

3.4.1.2. OFDM Transmission gain

Transmission gain adjustment is needed to prevent receiver saturation and to provide best channel correction performance. A desired level of gain variation between received OFDM symbols from different CPE is less than 3dB. The actual level is an implementation issue.

Gain adjustment is done in two modes:

1. Initial adjustment – A single CPE transmits a TBD fixed pilot pattern in the pre-allocated OFDM symbol. A complete BW of the OFDM channel is applied for initial synchronization. The WMTS detects the pattern and calculates the gain deviation. If the WMTS can’t detect the pattern it requests a gradual gain increase until detection is facilitated. An ID message is embedded into the OFDM symbol.
2. Continuous tracking – From every received OFDM symbol, from any CPE, the gain error is calculated and updated.

The WMTS reports back to the CPE the required correction.

3.4.1.3. Transmission gain

Transmission gain adjustment is needed to prevent receiver saturation and to provide best channel correction performance. A desired level of gain variation between received OFDM symbols from different CPE is less than 3 dB (TBD).

Gain adjustment is done in two modes:

1. Initial adjustment – A single CPE transmits a training signal with embedded ID message. The WMTS detects the training pattern and calculates the gain offset.
2. Continuous tracking – calculated continuously from the training pattern..

The WMTS reports back to the CPE the required correction.

4. Performance (normative)

4.1. FEC

4.1.1. BER performance

The table below gives the design performance for the FEC protocol.

	Performance QEF BER=10^{-11}		
Modulation	Code	Gaussian channel dB c/n	
QPSK	1/2	3.1	
QPSK	2/3	4.9	
QPSK	¾	5.9	
QPSK	5/6	6.9	
QPSK	7/8	7.7	
16-QAM	1/2	8.8	
16-QAM	2/3	11.1	
16-QAM	¾	12.5	
16-QAM	5/6	13.5	
16-QAM	7/8	13.9	
64-QAM	½	14.4	
64-QAM	2/3	16.5	
64-QAM	¾	18.0	
64-QAM	5/6	19.3	
64-QAM	7/8	20.1	

4.1.2. Channel capacity

The table below gives nominal capacity for 2K FFT in a 6 Mhz channel with 0.95 channel occupancy.

Channel parameters:

Channel = 6 Mhz

BI = 60 sub-carriers

Active sub-carriers = 1738

Data carrying sub-carriers = 1440

Sub-carrier bandwidth = $6E^6$ * 0.95 / 1738 = 3280 Hz

Clock rate : 3280 * 2K = 6,717440 Hz

RS = (204,2*8)

	Capacity for 2K FFT, Mbits/sec				
Modulation	Code	1/4	1/8	1/16	1/32
QPSK	1/2	3.48	3.86	4.14	4.22
QPSK	2/3	4.64	5.16	5.46	5.65
QPSK	¾	5.22	5.8	6.14	6.33
QPSK	5/6	5.8	6.44	6.83	7.03
QPSK	7/8	6.09	6.77	7.16	7.39
16-QAM	1/2	6.96	7.74	8.16	8.84
16-QAM	2/3	9.29	10.3	10.9	11.3
16-QAM	¾	10.4	11.6	12.3	12.7
16-QAM	5/6	11.6	12.9	13.6	14.1
16-QAM	7/8	12.2	13.5	14.3	14.8
64-QAM	½	10.47	11.6	12.3	12.7
64-QAM	2/3	13.9	15.5	16.4	16.9
64-QAM	¾	15.7	17.4	18.4	19
64-QAM	5/6	17.4	19.3	20.5	21.1
64-QAM	7/8	18.2	20.3	21.5	22.2
64QAM	non	20.8	23.2	24.5	25.4

EQAM vs. EOFDM capacity – The EQAM uses a training signal at a duty cycle of about 3%. This is equivalent to capacity loss of EOFDM guard when operating with 1/32 guard. The EOFDM has an additional loss of 16% due to the pilots. Channel occupancy in EOFDM is about 95% and EQAM is 89%. The contribution of the framing is equal to both modulations. Adding all this numbers implies 8% capacity advantage of EQAM over EOFDM.

4.1.3. Adaptive Modulation Capacity

The capacity increase by the use of adaptive modulation can be calculated for the simple nominal cases only. In actual field conditions the variants of parameters will results in capacity improvements that can be above or below the nominal case.

A simple case of capacity increase is given as example for suburban terrain. The capacity increased is based on dense cells where the interference of adjacent cells becomes dominant relative to other interferences that may results from low signal and therefore link budget. The structure of the cell pattern dictates the density of the cells but dose not affect the calculation of this interference model. The model also treats only the average performance and not the effect of each specific location in the cell.

Basic parameters:

Fading model - based on distance to the power of 3.5

Minimal reception quality at the edge of the cell to provide service:

C/n=10dB

Minimal reception quality at the edge of the cell to provide QAM16 service:

C/n=16dB

Minimal reception quality at the edge of the cell to provide QAM64 service:

C/n=24dB

Uniformly spaced CPEs in the cell.

Based on the fading model:

$$\text{Path loss(dB)} = 10\log[\,(d/d_0)^{3.5}]$$

It is possible to calculate the fractional radius at which C/n is at least 16dB based on C/n=10dB for the radius of 1.

The calculations yields:

R = 1 → C/n=10; R = 0.67 → C/n=16; R = 0.4 → C/n=24;

The capacity of the integral of the 3 circles is compared to the basic system where all CPEs are served by QPSK that provides the required service with no adaptive modulation.

By calculating the integral of M=2,4,6 bits for every circle the increased capacity is calculated to be 160%.

The contribution of the adaptive modulation was modeled here with flat fading only. The increase in capacity of 60% was calculated with flat fading of 16dB, from inner circle to outer boundaries of the cell. The adaptive modulation also compensates for local fading of 6dB more, thus increasing the capacity benefit even more.

Managing of the adaptive cost about 5% loss due to average loss of ½ of last BI capacity and due to the header and Sync content.

4.1.4. QoS

In the process of packing data into data segment and reporting the structure of data in the Sframe there is an inherent delay. This cause of delay exists in the downstream only. In the upstream each PDU is delivered upon reception from the MAC with the addition delay of the OFDM processing. FDMA on the upstream can provide dynamic allocation of bandwidth with average capacity that may reach the maximum peak capacity of the channel.

4.1.4.1. Super-Frame Latency

The latency is developed by the following steps is the Sframe construction: organizing data into data segments, duration of one Sframe and the requirement for the header to report the structure of the next Sframe. In EOFDM the maximal latency is generated when a PDU is fragmented, or when a PDU arriving relatively at the start of the Super-Frame transfer from the MAC, and is placed at the last section. In both cases the latency is up to three Super-Frames. In EQAM format, the maximal latency, is generated when a PDU, which arrived at the start of the Super-Frame transfer from the MAC, is placed in the continues section. In the worst case this PDU can be transmitted at the end of the following Super-Frame, generating a latency of four Super-Frames.

In an example case of using 6 frames of 2K FFT in a Sframe with a guard of $1/8^{th}$ the duration of each Sframe is 2msec. To this one has to add the OFDM processing which may account to 2msec more (total of HUB and CPE processing). The total delay is thus 8 msec in the EFODM case. This latency is equivalent to the latency of the byte interleaver that is used without the adaptive modulation.

The latency in the upstream is much shorter. It accounts for the delay of the OFDM processing. In the same example of 2K FFT, the total delay is of up to 6 OFDM symbols which accounts to only 2msec.

4.1.4.2. Dynamic channel allocation

In the downstream the link peak capacity for any CPE is achieved when the full BW is allocated for a particular CPE. The peak capacity may thus reach the average capacity at the specific modulation level and may exceed the average capacity of that channel if the targeted CPE can receive high modulation level.

In the upstream every CPE may use the whole BW for transmission. Although from the consideration of RF limitations CPEs that are required to transmit at full power may limit their BW of transmission. Other CPE may ask for the complete BW (in example 6Mhz channel) as long as the transmission power does not exceed the RF limitations.

4.1.5. Multipath

Delayed spread coverage requirements may change with the size of the cell. Some channel models report delay spread of up to 10μsec with Doppler of 2Hz. Each reflection can be at 0dB and the sum of all reflection can account for negative K factor.

Two parameters affect the channel correction in OFDM. A long enough guard is needed to prevent ISI. And enough pilot density is needed to interpolate the channel model. The interpolation algorithm is an implementation issue.

In a simple interpolation scheme 4 pilots per notch cycle give only 16dB. An increase of the pilot density can improve the interpolation accuracy.

Example 2K FFT mode:

6 Mhz channel is sampled at about 6.6 Mhz providing 0.95 channel coverage and requiring at least 4 pilots per notch cycle.

Up stream:

(1/6.6e6) * 2048 /(6*4) = 13 micro second coverage.

Down stream:

(1/6.6e6) * 2048 /(3*4) = 26 micro second coverage.

With a shorter FFT at the same sampling the coverage reduces linearly as presented below:

FFT length	Up stream (effective pilot density 1/6)	Down stream (effective density pilot 1/3)

		pilot 1/3)
2K	13 μsec	26 μsec
1K	6.5 μsec	13 μsec
512	3.25 μsec	6.5 μsec
256	1.8 μsec	3.25 μsec

The guard interval required to provide ISI protection is 1/16, thus implying only 6% loss of BW.

4.1.6. Phase noise requirements

Phase noise requirements for the OFDM based systems takes in account all the accumulated phase noise in one link. That includes modulator, up-converters, and receivers down conversion stages. Most sensitive is the reference oscillators and the PLLs in the CPE side of the link where cost considerations limits performance.

The Phase noise is integrated to yield the effective noise interference to the signal. The interference level is measured in C/n dB. Three interference levels are evaluated here: –35dB, –32dB and –28dB.

Phase noise requirement from the RF system is a system implementation issue that depends on all other source of interference.

One can consider the margin of phase noise level relative to threshold level of FEC:

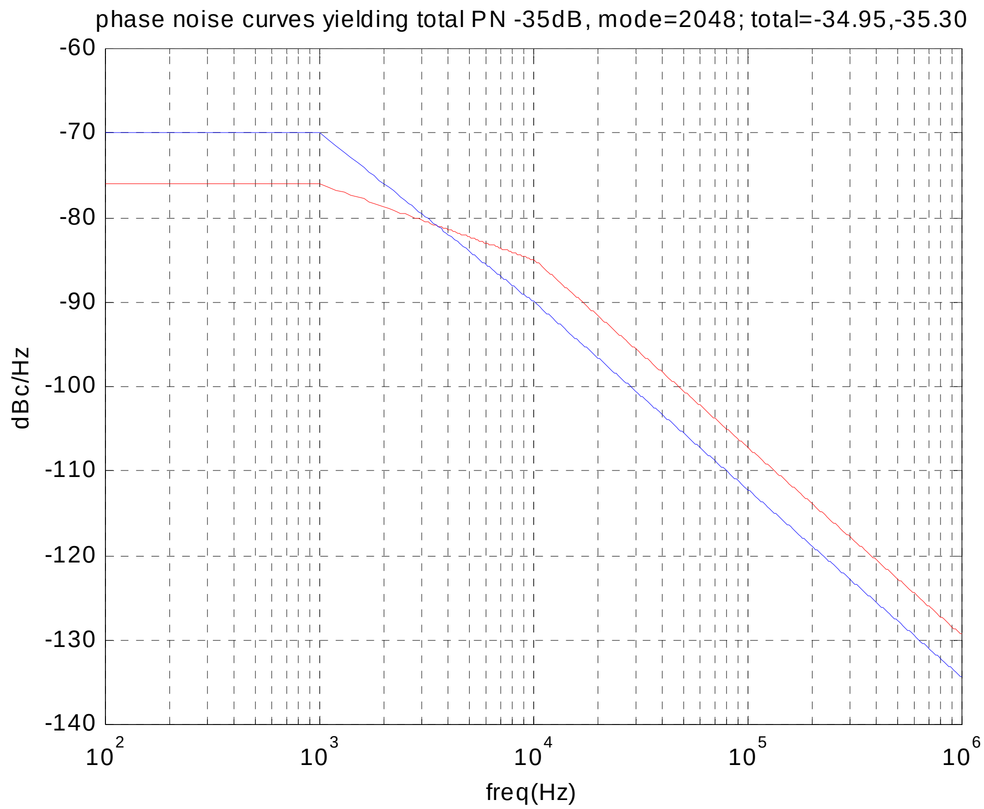
No effect on performance - 12 dB margin

If major cause of interference: 6 dB margin

For QAM64, profile 6, the 35dB C/n is 12dB above threshold thus causing no degradation in performance.

For QAM16, profile 3, the 28dB C/n yields no degradation.

Three phase noise curves yielding total phase noise of –35dB with FFT block length of 2048 are presented below. The blue curve shows nominal requirement while the red curve presents a different balance of the phase curve while keeping the same C/n effective interference.



The following table contains the phase noise (in dBc/Hz) allowed at several frequencies for three required conditions (total phase noise of –32, –35 and –28 dB, FFT block length of 1k and 2k):

Freq (kHz)	2k block length, total phase noise –35dB		2k block length, total phase noise –32dB		2k block length, total phase noise –28dB	
1	-70	-76	-65	-69	-59.5	-62
2	-76	-79	-73	-74	-69	-69
5	-84	-82	-82	-80	-81	-78
10	-90	-85	-90	-85	-90	-85
20	-97	-92	-96	-91	-96	-92

Freq (kHz)	1k block length, total phase noise –35dB	
1	-65	-71
2	-73	-75
5	-82	-81
10	-90	-85
20	-96	-92

5. Appendix A

An optional pilot configuration on the downstream where a pilot is inserted every 12th position. Each OFDM symbol the pilots are moved by 3 sub-carriers such that in 4 OFDM symbols an effective pilot is inserted every 3rd position. In this configuration there is an 8% increase in downstream capacity. The sync is shortened and no low rate bits are employed.

Downstream pilots allocation:

FFT	Zeros [left, right]	Fixed pilots position	Scattered pilots	Data sub-carriers	Sync	BI size
2K	158,158	1, 1732	13:12:1729 10:12:1726 7:12:1723 4:12:1720 144 pilots	1584 =24*66	4	66
1K	78,78	1,868	13:12:865 10:12:862 7:12:859 4:12:856 72 pilots	792 12*66	4	66
512	38,38	1, 436	13:12:433 10:12:430 7:12:427 4:12:424 36 pilots	396 6*66	4	66
256	18, 18	1, 220	13:12:217 10:12:214 7:12:111 4:12:108 18 pilots	196 3*66	4	66

6. Appendix B

Evaluation Criteria for MMDS PHY

The PHY proposal addresses the requirements of delivering digital data in the terrestrial environment. The reception conditions are normally characterized by complex delay spread and flat fading.

FRD requirements:

Scalability – delay spread handling with 256 - 2K FFT provides conditions from small to supper-cells environment.

Data framing – A single FEC structure for up and down stream with simple link layer to existing MAC data interface.

FEC – Concatenated FEC with standard convolutional (133,171) and RS encoding, with dynamic FEC rate and modulation level.

Modulation – OFDM based modulation is recommended. However, the data framing proposed here is very easily applied to single-carrier systems as well.

EOFDM – provides adaptive modulation OFDM modulation.

Peak rate – using adaptive modulation channel facilitating allocation of full BW to one user, thus achieving maximum peak capacity.

Spectral efficiency – adaptive modulation enables maximum spectral efficiency by individually adjusting operating parameters to every CPE.

Flexible Asymmetry – In FDD: dynamic allocation of BW enables more flexibility in BW allocation. In TDD the protocol supports flexible TMDA access.

Delays – Down stream adaptive modulation operates with delay equivalent to continuous SC protocols. On the uplink the dynamic allocation of BW can shortened the delay relative to fix BW systems.

Capacity – Average capacity increase by the use of adaptive modulation can reach 60%.

Duplex mode – FDD and TTD are supported.

Channelization – The framing been independent of channel BW.

Channel Spectrum Efficiency:

Adaptive modulation – increase of 60% compare to single modulation use.

Modulation of a single data segment with EOFDM: 0.6-4.2 Bits/sec/Hz on 6 Mhz channel.

Down stream adaptive modulation with expected increased capacity: 0.9 – 6.72 Bits/sec/Hz.

Upstream capacity - 0.6-4.2 Bits/sec/Hz on 6 Mhz channel.

Occupied BW – With EOFDM 0.95

Simplicity of Realization:

FEC – the use of existing concatenated coding. Proven technology.

OFDM – based on the DVB-T modulation. Proven technology.

Adaptive modulation - simple implementation and addition to existing IC technology..

Upstream FDMA – reducing the need for uplink channel splitting, thus HUB cost.

Installation cost - powerful OFDM and FEC implies non-line of sight installation.

Spectrum Resources Flexibility:

Adaptive modulation with FDMA on the upstream provides maximum average and peak capacity and channel usage.

FDMA eliminates the need for uplink channel splitting.

The use of this PHY is not limited to any specific channel allocation and BW.

The use of adaptive modulation provides dynamic flexibility for QoS and eliminates the need for a fixed and compromising average performance.

System Service Flexibility:

The proposed PHY is extremely flexible to facilitate various operation conditions. The PHY provides means to remotely changing the system operating parameters with no need for fixed pre-setting of the modem.

Protocol Interfacing Complexity:

The PHY can support any length of data bursts in TDD and FDD. It interfaces to the MAC with existing link layers.

Robustness to Interference:

Proven FEC scheme with adaptive modulation enabling continuous operation and service in C/n from 28dB down to 3.5dB, while keeping high average data capacity.

FDMA can selectively allocate BW and sub-channels according operating conditions.

Robustness to impairments:

Delay spread – powerful OFDM technology for non-line of sight conditions. EOFDM can handle 0dB reflections with 0dB and below K factor, with delay spread of up to 23 micro-sec. The EOFDM (proven by DVB-T) can handle up to 200Hz Doppler shift.

Radio impairments:

Radio impairments typically difficult for OFDM modulation can easily hndled by the flexibility of the EOFDM specifications. Phase noise sensitivity can be reduced by short FFTs while amplifier linearity and distortions are handled by signal post-filtering and amplifier pre-correction.

Support for advanced antenna techniques:

EOFDM as any OFDM modulation is well suited for the implementation of diversity algorithm and smart antennas.

Compatibility:

The EOFDM is based on the OFDM modulation of the DVB-T. Common FEC scheme is used. A simple link layer provide interface to existing MAC protocols.