An emission/reception chain modelling of the WiMAX access network

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***Abstract* — This work describes the simulation under the Simulink environment of Matlab of an IEEE802.16 complete transmitter/receiver chain. Because of its superior performance the WirelessMAN OFDM 256 PHY layer is the most implemented in WiMAX compliant devices. The first part of the paper concerns the validation of a transmitter model using that PHY layer while the second part of the article deals with a complete transmitter/receiver model proposed. An example with a 20 MHz channel using adaptive modulation is considered and analyzed. This model takes into account several constraints and problem of the standard translation: reducing ambiguity in the standard and providing a reference for compliance testing.**

Index Terms— 802.16, MATLAB, access network, PHY layer, wireless network

1 Introduction

The IEEE 802.16 Standards are a family of standards designed to establish interfaces for fixed, portable and even mobile Broadband Wireless Access (BWA) systems. In the first part of this article we describe how we have performed our validation (capture implementation, test) using Simulink. The validation model presented is designed as an interactive Simulink test file. In the second part of the article we present simulations of an entire 802.16 emission/reception chain.

2 Interpreting the standard

2.1 Brief history

The first version of the 802.16 standard was released in October 2001. The specification described a Single Carrier air interface for fixed point-to-multipoint (PMP) BWA systems operating between 10-66 GHz [1].

Next amendment, 802.16a (2003) extends the physical environment towards lower frequency bands below 11 GHz. Moreover the amendment defines two other physical interfaces in order to fit this new frequency band: the WirelessMAN OFDM PHY and the WirelessMAN OFDMA PHY. While the first is using a 256-carrier Orthogonal Frequency Division Multiplexing (OFDM), the second is using a 2048-carrier Orthogonal Frequency Division Multiple Access (OFDMA) scheme [2]. An optional mesh topology is also added to the mandatory PMP architecture.

The most recently approved version 802.16-2004 [3], enables us to have a comprehensive reading of the standard incorporating previous versions and amendments. The last amendment 802.16e-2005 [4] released on February 2006, propose a modification of Physical (PHY) and Medium Access Control (MAC) Layers described by 802.16-2004 for Combined Fixed and Mobile Operation in Licensed Bands.

While 802.16e [5] was amended, the first products to complete the rigorous test procedures required for 802.16-2004 certification have been released on the market. The WiMAX Forum is responsible for the interoperability of WiMAX devices, the certification being based on the 802.16 Standard document. The document, about 900 pages long, is describing in detail PHY and MAC layers for WiMAX systems, guaranteeing the compatibility and interoperability between broadband wireless access components.

However the complexity of the standard makes it difficult for designers to create standard-compliant components. For this kind of problems model-based simulations using network simulators often come to the rescue of designers. Although network simulators like Opnet, Network Simulator 2 (NS2), Qualnet, etc…, allow a network entire representation describing precisely the channel and upper layers of the OSI Stack representation, the PHY layer and specially real component constraints aren't well taken into account. That's why we have chosen the Simulink tool under the MATLAB environment to validate our system. The standard is the key element of the model development process but as in every document-based design product, every translation or new amendment can introduce errors and omissions. These errors can have a tremendous importance in compliance testing that is why we have decided first to design a validating tool for WiMAX compliance testing.

2.2 Simulink validating tool

Because of its superior performance in multipath fading wireless channels [6], the WirelessMAN OFDM 256 PHY layer is the most implemented in WiMAX compliant devices. That is why, the PHY layer we are going to validate is this one. In the rest of the paper we will only talk about this interface.

Unlike many other OFDM-based systems such as 802.11 [7], the 802.16 standard supports variable bandwidth sizes between 1.25 and 20 MHz. This feature and the support of combined fixed and mobile usage models, require a scalable OFDM signalling protocol.

Although the problem of the translation of the WiMAX standard into a Simulink model is a difficult job, the section 8.3.3 of the 802.16 standard gives some ways to handle the job dividing it into three steps: data randomization, forward error correction (FEC) and interleaving. In order to have a good understanding we include in our model the modulation and the OFDM symbol creation.

2.2.1 Randomization

Randomization is performed by a Pseudo Random Binary Sequence PRBS. The generator polynomial of the PRBS is $1+X^{14}+X^{15}$.

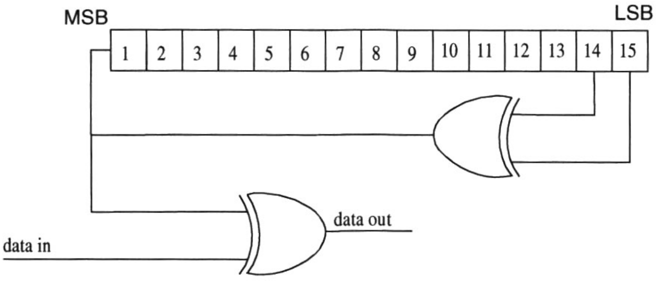

Figure 1. PRBS Generator

Under the Simulink environment the randomization is performed by a PN Sequence Block. The initial state of the PN sequence is given in all test sequences. It is also important to note that a ‘0x00’ tail byte is appended after the randomization

2.2.2 Forward Error Correction

The FEC consists of the concatenation of a Reed-Solomon outer code and a rate compatible convolutional inner code. The support of block and convolutional Turbo Codes are optional. The encoding is performed by first passing the data in block format through the RS encoder and then passing it through a zero-terminating convolutional encoder.

Reed Solomon codes are a subset of Bose, Ray-Chaudhuri, Hocquenghem

(BCH) codes and are linear block codes. A Reed-Solomon code is specified as RS(*n, k, t*).

This means that the encoder takes *k* data symbols and adds parity symbols to make an *n* symbol codeword. The code rate is Rc= k/n and *n-k* parity symbols are added. A Reed-Solomon decoder can correct up to *t* symbols that contain errors in a codeword, where $2t = n-k$. This is known as a Systematic code because the data is left unchanged and the parity symbols are appended. The amount of processing "power" required to encode and decode Reed-Solomon codes is related to the number of parity symbols per codeword. A large value of t means that a large number of errors can be corrected but requires more computational power than a small value of t.

The standard states that the Reed-Solomon encoder is derived from a systematic RS(255, 239, 8) code using shortening techniques in order to achieve different rates. Reed-Solomon shortening consists in inserting a number of data symbols zero at the encoder, not transmitting them, and then re-inserting them at the decoder.

A convolutional code is generated by passing the information sequence through a linear finite state shift register. In general the register consists of K stages and n linear algebraic function generators. The parameter K is called the constraint length and the code rate is Rc=1/n.

In our case the data is then encoded by the binary convolutional encoder with a native rate of 1/2, a constraint length equal to 7 and polynomials codes given in octal: G1=171, G2=133. The code is then punctured with a mask in order to achieve the good redundancy.

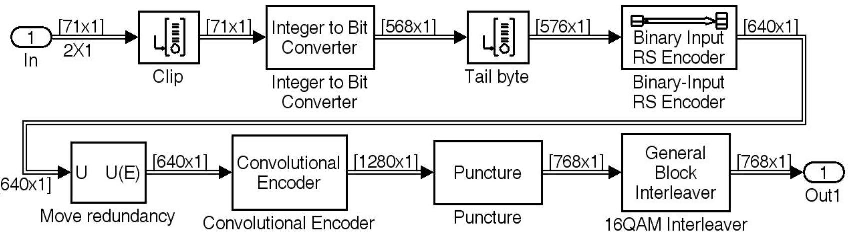

Figure 2. System overview

2.2.3 Interleaving

The standard defines the interleaver using a pair of permutation:

$$m_k = (N_{cbps}/12).k_{\mathrm{mod}12} + floor(k/12) \tag{1}$$

$$j_k = s.floor(m_k/s) + (m_k + N_{cbps} - floor(12.m_k/N_{cbps}))_{\mathrm{mod}(s)} \tag{2}$$

$$s = ceil(N_{cpc}/2) \quad ; \quad k = 0,1,\cdots,N_{cbps} - 1$$

With N_{cbps} being the number of coded bits per subchannel, N_{cpc} the number of coded bits per carrier.

The first ensures that adjacent coded bits are mapped onto nonadjacent OFDM subcarriers and the second map adjacent coded bits alternately onto less or more significant bits of the constellation. It is important to note that m_k and j_k are write addresses and *intrlv* MATLAB function need read addresses. This problem is solved using the *sort* MATLAB function to obtain the required permutation vector. Once we have the good permutation vector we can use the General interleaver block of the Communication blockset library of Simulink [8].

This kind of problem is typically a source of errors due to the standard translation, and without the test vectors the implementation wouldn't have been seen in bit error rate (BER) analysis and other system-level tests but it would have produced a non-interoperable device.

2.2.4 Modulation and OFDM symbol creation

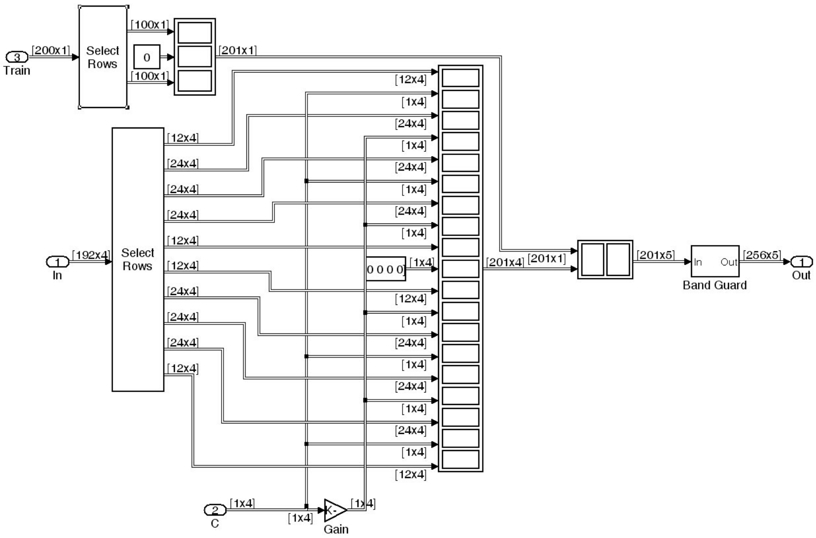

Figure 3. OFDM Symbol creation

After bit interleaving, the data bits are passed through the constellation mapper. Four constellations are defined BPSK, Gray mapped QPSK, 16QAM and 64QAM. 64QAM is optional in unlicensed frequency bands. The constellations are normalized with a factor to achieve equal average power.

Once data is correctly mapped the data has to be modulated onto all allocated data subcarriers according to the order of increasing frequency offset index. This job is performed by the FFT block. However before this stage pilot subcarriers should be inserted. A preamble can also be inserted in order to simulate a short frame.

The value of the pilot modulation is generated by a PRBS generator with the generator polynomial $1+X^9+X^{11}$. The value is then complemented according to the subcarrier index.

The result of all this succession of operations is a vector of 200 complex numbers, representing amplitude and phase information of the associated subcarrier created by the FFT block.

2.2.5 The validation stage

The validation is performed by passing the test vector into the Matlab environment and then verifying at each step the output of all precedent blocks. Fig.4 shows the validation of our transmitter with the first test vector given by the standard. This first WIMAX test vector is a 35 byte long data vector given in hex notation. This example using the pair modulation/coding QPSK-3/4, doesn't use subchannelisation and all initial states of the Pseudo Random Binary sequence PRBS used are well described.

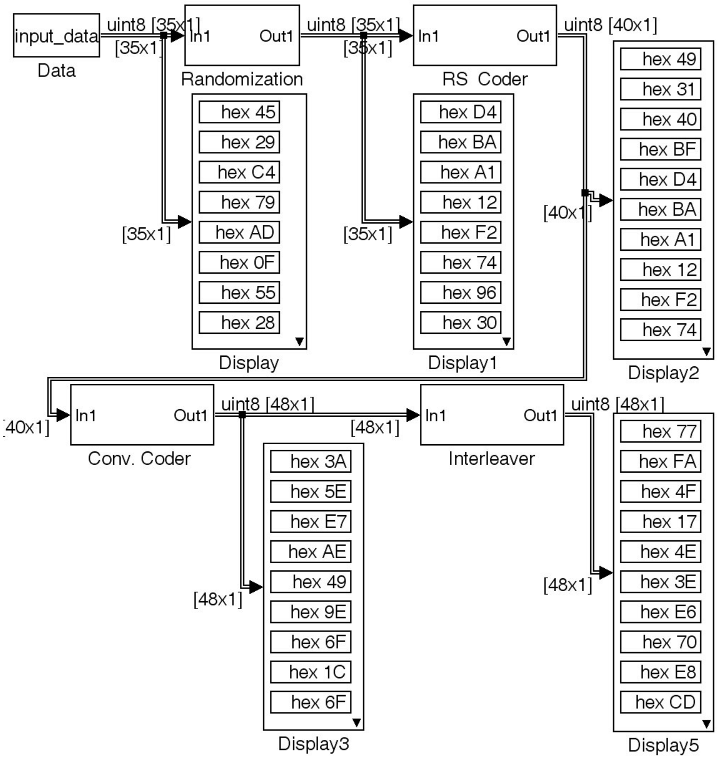

Figure 4. Validation stage

Once we have validated a test sequence we are now going to generate data continuously.

3 Receiver design

Like most communication standards, 802.16 specifies the signal processing in the transmitter only. This enables manufacturers to have an implementation margin without sacrifying interoperability. Once we have a complete Simulink model of the WiMAX transmitter, we are going to design a standard compliant receiver. The Fig.5 shows the complete model.

3.1 *Structure of the model*

This section is going to describe block by block the structure we have implemented, assumptions we have made and other simplifications we have performed.

3.1.1 Data Source

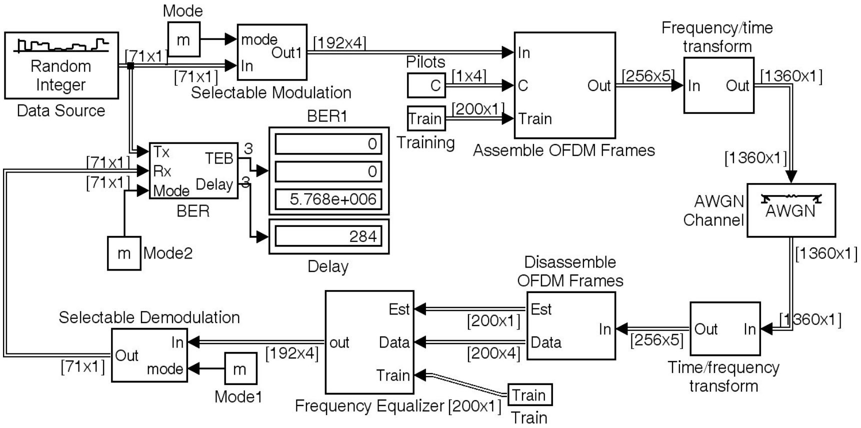

Figure 5. Complete system

The generation of random data is now achieved by a random integer generator. The generator creates a fixed frame of 71 bytes with a bit frame time of 12 µs when using a channel bandwidth of 20 Mhz. This time corresponds to the symbol time defined by the 8.3.2.2 section of the standard.

$$F_S = floor(n.BW/8000).8000 \tag{3}$$

$$T_S = (1+G).1/\Delta f \qquad with\ \Delta f = F_s / N_{FFT} \tag{4}$$

If the pair modulation/coding requires a different amount of data the random data is clipped according to the standard. This operation is performed inside the modulation block.

3.1.2 Coding, interleaving and modulation

Modulation/coding	Ncbps	Throughput
BPSK	96	8 Mbit/s
QPSK1/2	192	16 Mbit/s
QPSK3/4	288	24 Mbit/s
16QAM1/2	384	32 Mbit/s
16QAM3/4	576	48 Mbit/s

Table 1. Throughput

The coding, interleaving, and modulation are simulated according to the standard. In particular, each modulator block performs these tasks: convolutional coding and puncturing using code rates of 1/2 and 3/4, data interleaving, BPSK, QPSK and 16-QAM modulation.

Each pair modulation/coding corresponds to a specific rate. If we keep the same conditions as above rates are summarised in the table 1.

The number of data symbols in each packet has been fixed to four OFDM symbol per frame. Pad bits have been omitted and buffering for frame transmission is performed at the end of the block.

3.1.3 Transmission, channel and equalisation

OFDM transmission uses 200 subcarriers, 8 pilots, 256-point FFTs, and a 16-sample cyclic prefix. The channel block is configurable as a simple AWGN channel or a dispersive multipath fading channel. However for simplicity, we have fixed the transmit power level to 1W.

The receiver equalization is based on a standard frequency-domain equalization. The principle is, in a first step, to find the transfer function of the channel for each subcarrier H(▯). This operation is performed by a comparison of well known training sequences. And then multiplying the data by 1/H(▯) annihilating phase and gain in the subchannel, considered flat.

3.1.4 Demodulation, deinterleaving and decoding

The demodulation and decoding block perform the inverse operations of modulation and coding. The decoding of the convolutional coding is performed by a Viterbi algorithm.

Also, the simulation model does not model these aspects of the IEEE 802.16 standard: data scrambling, which is unnecessary in this model because the data is random, subchanelisation and time windowing of OFDM symbols

3.2 Test mechanism and validation of the transmitter/receiver chain.

Tests and validation presented in this paragraph were made with a manual selection of Modulation/Demodulation in order to qualify each pair coding modulation.

3.2.1 Test mechanisms

For our experimentation we ran simulation and sent 10 Mbits of data by the Data source described above. The pair modulation/coding has been selected manually and the channel chosen for characterization was an AWGN channel.

For each pair modulation/coding we have performed several measures of the residual BER after correction, varying the SNR.

3.2.2 Validation of the reception chain

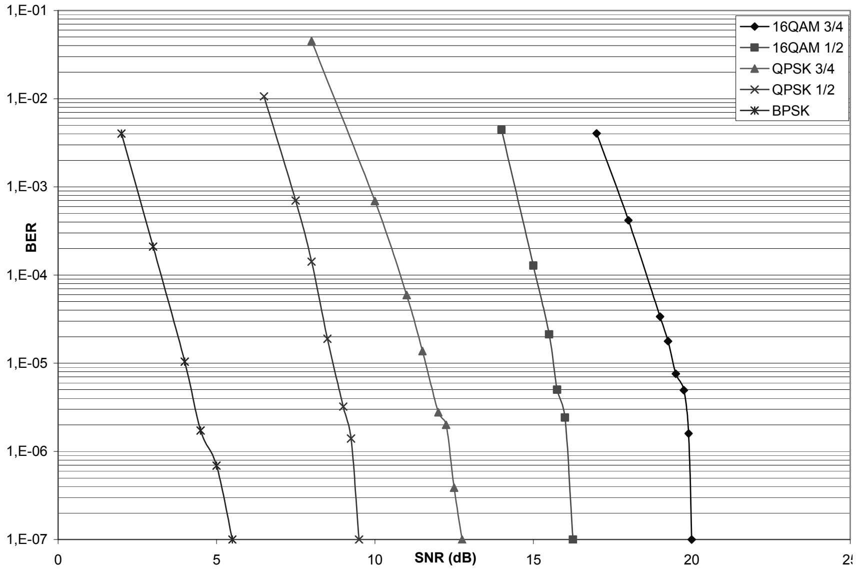

Figure 6. Residual BER varying SNR

The Fig.6 gives the result of our experimentation. This figure describes how the BER after FEC evolves when the SNR, modelled in the channel block, increase for different pairs modulation/coding.

The chapter 8.3.11 of the standard gives several constraints about the receiver sensitivity. The most important criterion is the residual BER after the FEC. Under several conditions such as an AWGN, in calibrated environments, certain packet formats and SNR assumptions, the standard defines a minimum residual BER of 10^{-6} at a given power level.

This power level is given by the equation:

$$R_{SS} = -102 + SNR_{Rx} + 10.\log(F_S.\frac{N_{used}}{N_{FFT}}.\frac{N_{subchannels}}{16}) \qquad (5)$$

With SNR_{Rx} being the SNR assumption in Table2, F_S being sampling frequency Eq(3), $N_{subchannels}$ the number of allocated subchannels.

Our approach is quite the same; since we have fixed our input signal strength to 1W we are going to verify SNR assumptions. The results show that all assumptions aren't verified especially the assumptions made for coding efficiency of 3/4 while pairs using a 1/2 redundancy satisfy easily their assumptions. However it seems that residual BER of 3/4 coded pairs decrease less quickly when the SNR goes down than 1/2 coded.

We can conclude for this first experiment that, apart from some assumptions and simplifications of the model, the receiver can be validated as a 802.16 compliant model. Although the chapter 8.3.11 of the standard gives several other constraints such as maximum input and maximum tolerable signal for the receiver, these parameters aren't modelled since our Simulink blocks are considered ideals. The table 2 presents a comparison between SNR assumed by the Table 266 of the standard and those measured by our model.

Modulation	SNR assumed	SNR with 10^{-6} BER	R_{SS}
BPSK	6,4 dB	4,7 dB	-23,1 dB
QPSK1/2	9,4 dB	9,2 dB	-20,1 dB
QPSK3/4	11,2 dB	12,5 dB	-18,3 dB
16QAM1/2	16,4 dB	15,9 dB	-13,1 dB
16QAM3/4	18,2 dB	19,8 dB	-11,3 dB

Table 2. Verifying SNR assumptions

3.3 Adaptive Modulation

The ability of WiMAX networks to offer a high performance within elevated distance with high spectral efficiency and signal tolerance is based on a strong adaptive modulation mechanism. This first experiment has fixed the border of each pair modulation/coding, now we are going to describe how the switching is done.

3.4 Channel quality estimating

Channels with variable signal-to-interference plus noise ratio (SINR) often use, like 802.11[9], several adaptive data rate schemes for increasing throughput[10]

These variations of SINR due to path loss, fading, or interferences have to be taken into account in order to satisfy the minimum BER fixed by the 802.16 standard. The symbol rate being fixed, the throughput may be varied by changing the bandwidth efficiency (bits/symbol) using a choice of coded modulation schemes. This variation may be assumed or coded systems by fixing the modulation and varying the code rate. Another possibility is to fix the code rate and adapt the constellation size. The last possibility, and it is our case, is to make a combination of the two former possibilities defining pairs modulation/coding and switching between them. It is also important to note that quality measurements are also essential for purposes of handoff and power control

In an OFDM system, the temporal comparison of ideal and corrupted signals can be replaced by comparing the modulation symbols, which is performed in frequency domain.

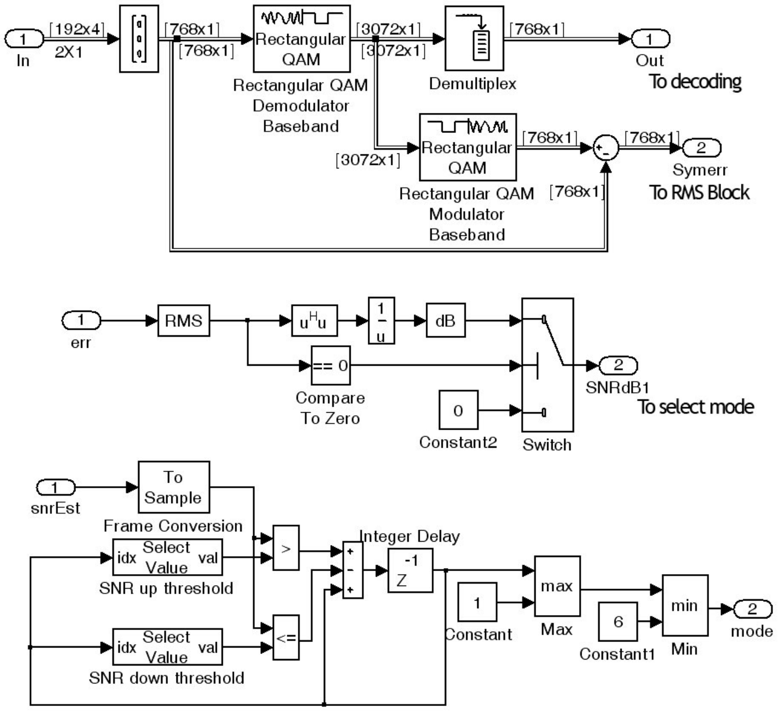

Figure 7. Quality estimation

The noise $Z_{n,k}$ for the kth sub-carrier of nth OFDM symbol can be formulated as [11]:

$$Z_{n,k} = Y_{n,k} - S_{n,k} H_{n,k} \tag{6}$$

Where $S_{n,k}$ is the noiseless sample of the received symbol and $H_{n,k}$ is the channel estimate.

The computation is quite simple for an OFDM system, since a large frequency offset is not likely due to the frequency synchronization requirement of the OFDM system itself.

Under Simulink environment, the signal is received along with noise and interference by the demodulator block. After the demodulation, the ideal signal is remodulated using the same modulation. The complex sum is then computed and passed through the RMS block computing the quality.
The figure 7 describe the system

The channel quality estimated is then passed through the adaptive mode selection block selecting according to SNR threshold defined above.

3.5 Running the model

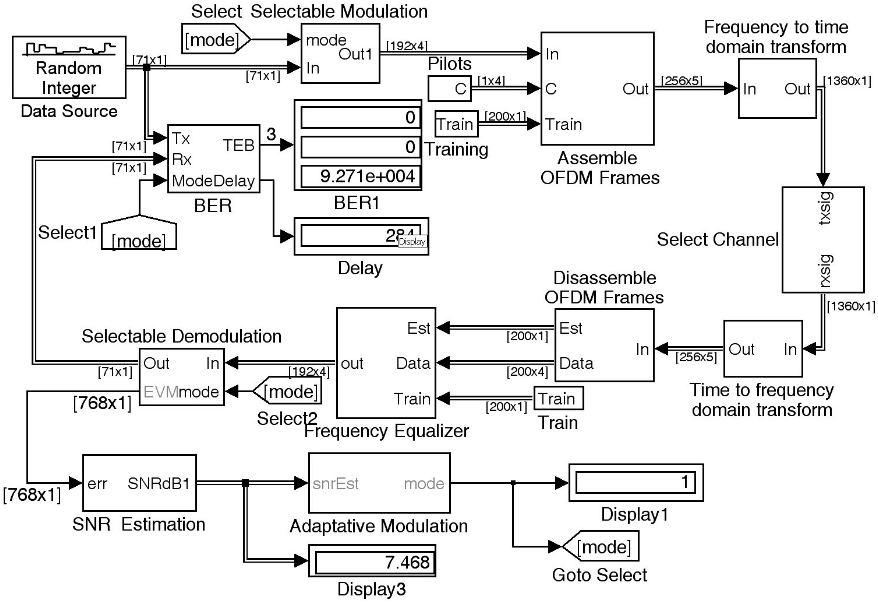

Figure 8. Adaptive Modulation

The complete model shown in Fig. 8 runs without any manual selection. Tests of the model using an ideal channel have proved that no errors without BER calculation time window errors were measured. Using an AWGN channel and varying manually the SNR we have found the same results as in III.B.2). More experiments with a Rayleigh fading channel have only shown a well known weakness of

OFDM systems: the sensitivity to carrier frequency offset. This offset destroys the orthogonality of the sub-carriers, causing sub-carrier offset and Inter Carrier Interference (ICI).

4 Conclusion

The WiMAX wireless network is thought to be used as an access network for the “last mile” and few engineering tools are currently available for this technology. In this work, we have implemented in a first stage a 802.16 compliant transmission chain validated by test vectors described in the standard. In a second stage we have developed a receiver according to advices and constraints of the standard. We have noticed during the implementation that all the conditions weren’t observed due to our assumptions and simplification of the Standard. This work has been developed as an engineering tool to design 802.16 standard compliant devices because finally the 802.16 work group, as designers, confronts the challenge of standard translations. The best example is all amendments and corrigenda adopted in the 802.16 standard history. This model can help reducing ambiguity in the standard and providing a reference for compliance testing. In the continuation of this work, we envisage using these results including them in a PHY and MAC layer model. A work using a NS2 model of the 802.16 MAC framing is currently being performed in our laboratory. In a next stage, we aim at validating the WiMAX QoS mechanisms in order to assess the performances available for wireless Voice and Telephony over IP.

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