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Performance Analysis of HARQ in WiMAX Networks Considering Imperfect Channel Estimation

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***Abstract*— Hybrid Automatic Repeat Query (HARQ) is an error correction technique that has become an integral part of most current broadband wireless standards such as IEEE 802.16 and 3GPP-LTE (Long Term Evolution). Although extensive studies have been made on the performance of HARQ, they usually assume perfect channel state information at the receiver. This paper addresses the performance of incremental redundancy HARQ under the specifications of the physical layer of the WiMAX standard considering imperfect channel state information, such as the one obtained by channel estimation. Several combinations of modulation, channel code rates and information block size are considered, and a realistic physical channel model used for standardization is used throughout the simulations to evaluate the performance of HARQ. Results show that the link throughput can be severely degraded, specifically at low values of signal-to-noise ratio, and HARQ performance may be too optimistic if channel estimation is ignored.**

***Keywords*— channel estimation, HARQ, incremental redundancy, WiMAX.**

I. INTRODUCTION

Throughout the evolution of mobile communication systems, the search for techniques that take the most efficient use of the spectrum can be perceived as a common goal. Ensuring the transmission reliability over the mobile wireless channel is essential to meet the current demand for services, as well as those to be offered by future generation systems [1]. However, the wireless transmission of data, due to the nature of propagation, is affected by fluctuations in the instantaneous signal strength, leading to high error rates and low-rate data transmission, severely limiting the capacity that can be achieved.

Several techniques have been developed in order to improve the system performance by reducing the error rate in wireless communication systems. Wireless broadband networks such as IEEE 802.16 WiMAX (Worldwide Interoperability for Microwave Access), and 3GPP-LTE (Long Term Evolution) have several mechanisms that seek to minimize the effect of the channel fading on the performance, and thus provide almost error-free transmissions. Among these mechanisms, one can highlight HARQ (Hybrid Automatic Repeat Request), which tries to ensure reliable transmission through the retransmission of the corrupted data and the combination of the subsequent repeated versions at the receiver [2].

In particular to WiMAX, two mechanisms are used to provide reliable transmission: ARQ (Automatic Repeat Query) and HARQ. both mechanisms rely on the parity check to verify the data integrity, and on error correcting codes and retransmission to resend the packets that were lost or corrupted. The evaluation of IEEE 802.16 ARQ parameters was considered in [3]. In [4], the performance of ARQ and HARQ are compared using NS2 (Network Simulator 2) for the IEEE 802.16 standard.

In this paper, the performance of the HARQ retransmission mechanism for the IEEE 802.16-2009 standard known as incremental redundancy is evaluated. Through simulations, different modulation schemes and code rates are considered. Moreover, we also vary the size of the information blocks, as this is may have some significant influence on system performance.

HARQ has been extensively studied in the literature, for instance in [5]–[8]. However, to our knowledge, none of these has addressed the issue of non-ideal channel estimation. HARQ surely shows an enormous potential to improve system performance, as the post-combining signal-to-noise ratio (SNR) increases with every packet retransmission. However, when realistic channel estimation is considered, the situation may not be that favourable. If one or several of the retransmission are done under a very low SNR, this affects the channel estimation process, so that the information after demodulation may be much less reliable for each packet, than what would be the case with perfect channel estimation. This means that an analysis done under the ideal channel estimation assumption may be far too optimistic, because with HARQ we tend to transmit with lower SNR levels. In this paper we consider this situation.

Simulations were performed using WiSiL [9], a Matlab®-based link-level simulation platform for broadband wireless technologies developed in cooperation among the University of Braslia (UnB), Nokia Technology Institute (INdT) and the Federal University of Rio de Janeiro (UFRJ).

This paper is organized as follows. In Section II the basics of ARQ and HARQ are presented. A description of the physical layer of WiMAX is done is Section III. In Section IV we discuss the simulation results. In Section V are presented the concluding remarks.

II. ARQ AND HARQ

ARQ has been used for several decades to ensure reliable data transmission by retransmitting the corrupted data [2]. It is a control technique for the data-link layer in which the receiver demands the transmitter to send again the blocks of data in which errors are detected. The receiver verifies that the packet was received with errors using the CRC (cyclic redundancy check) code that is attached to each and every information block. After the CRC verification, the receiver sends either a positive acknowledgement (ACK) or a negative acknowledgement (NACK) concerning the reception of the data block. There are three well-known implementations of ARQ: stop-and-wait, go-back-N and the selective retransmission. The stop-and-wait ARQ is the simplest to implement, but implies in a lower system throughput when compared with the other schemes, especially for channels whose propagation delay is high.

The HARQ scheme combines two forms of coding for error control: FEC (forward error correction) and ARQ, making it possible to reduce the number of retransmissions, potentially increasing the system throughput when compared to systems that employ solely

ARQ. When HARQ is used, instead of discarding each erroneously received packet, these are stored at the receiver side and later combined with their respective retransmitted copies, increasing the reliability of the transmitted information. Two extensively investigated implementations are CC (chase combining) and IR (incremental redundancy) [10]. On CC, every retransmission contains the same information (data and parity bits). On IR, every retransmission contains different information from the previous ones. At every retransmission the receiver gains knowledge of extra information. This is usually achieved by changing the puncture pattern of the FEC coding on each retransmission [11].

III. WiMAX PHYSICAL LAYER

In the next subsections, the physical layer of WiMAX standard is briefly described. Further details and references can be found in [12].

A. Multicarrier Access

WiMAX physical layer is based on the IEEE 802.16-2009 standards, and uses multicarrier techniques for transmission, more specifically OFDMA (Orthogonal Frequency Division Multiple Access). In WiMAX the spacing between the subcarriers is fixed and equal to 10.94 kHz. Different bandwidths can be achievable by changing the number of subcarriers, which can assume the values 128, 512, 1024 or 2048, corresponding to bandwidths of 1.25, 5, 10 and 20 MHz respectively. The standards also allow different lengths of cyclic prefix, which can be 1/32, 1/16, 1/8 or 1/4 of the useful symbol length, but currently only 1/8 is required by the WiMAX profiles. OFDMA allows the access of multiple users simultaneously to the physical medium, and the variable amount of subcarriers enables the systems to operate under different transmission rates or bandwidth availability for system deployment.

The channel coding scheme can be either based on convolutional codes or turbo codes. LDPC codes are also specified, but not required. Once the coding is performed, the packets undergo a process of rate matching to adjust their length to the radio frame.

B. Subchannelisation

A slot is the basic resource allocation unit at the physical layer, and it consists of one subchannel at the frequency domain and one ore more OFDMA symbols. A subchannel includes a set of data and, sometimes, also pilot subcarriers (used for estimation and tracking of the channel frequency response). The exact number of subcarriers per subchannel as well as their allocation depends on the permutation mode. The subcarriers in each subchannel may be adjacent, as in the AMC (Adaptive Modulation and Coding) permutation scheme, or, more commonly, distributed all over the whole available spectrum, as in FUSC (Downlink Full Usage of subcarriers) or DL PUSC (Downlink Partial Usage of Subcarrier). Particular attention must be given to the latter, which is mandatory in every WiMAX frame.

The MAC (Media Access Control) layer allocates slots for the various users. The size of a slot also depends on the used permutation mode. For example, in DL FUSC, a slot consists on 48 subcarriers in the frequency domain and one OFDM symbol in the time domain. In DL PUSC each slot covers 24 subcarriers by two OFDM symbols. The data region is the contiguous collection of slots that are allocated to a single user.

C. Frame Structure

The frame duration is variable, allowing values between 2 ms and 20 ms, but only a 5 ms frame is currently mandated. In TDD mode, each frame is divided into a downlink and an uplink subframe. Each of these subframes may contain several zones, each consisting of a number of OFDMA symbols and using a different subcarrier permutation scheme. At the beginning of the downlink subframe, control messages are sent to indicate the start position of the zones and their duration. The first OFDM symbol is used to transmit a preamble for the purpose of synchronization and initial channel estimation. Channel descriptors and control messages are sent in the following symbols.

D. HARQ in WiMAX

The physical layer of the IEEE 802.16-2009 standards defines two modes of operation for the HARQ mechanism, namely CC and IR [12]. Here we briefly describe the IR mode.

As shown in Fig. 1, the MAC protocol data unit (MPDU), or a concatenation of MPDU's, is stuffed with 1's bits so that the length of the MPDU (or a concatenation of them) belongs to the set $\{4, 10, 16, 22, 34, 46, 58, 118, 238, 358, 598, 1198, 1798, 2398, 2998\}$ bytes. Then, a CRC field is added, so that the resulting length of data unit is in the set $\{6, 12, 18, 24, 36, 48, 60, 120, 240, 360, 600, 1200, 1800, 2400, 3000\}$ bytes. After a randomizer, the data unit called HARQ PSDU (physical data service unit) is generated, and it is further divided into 600 byte fragments before the FEC channel coding is performed on each fragment. Four subpackets are generated for each HARQ PSDU, which are then modulated and sequentially transmitted to the receiver.

The SPID (subpacket identifier) is used to uniquely identify each of the subpacket generated from each HARQ PSDU. This is necessary when the HARQ is operating in IR mode, since each subpacket contains different parity information generated by different FEC puncturing patterns. In CC mode, since the content of each subpacket associated with HARQ PSDU is the same, the SPID is not used.

When the receiver cannot decode the first subpacket, it sends a negative acknowledgment to the transmitter in the next subframe. The transmitter selects the next subpacket and sends it to the receiver. The retransmissions continue until the receiver can decode the HARQ PSDU correctly or until all retransmissions fail. In the latter case, the HARQ PSDU is considered not successfully delivered after the HARQ process, and it is up to the upper layers the decision of either retransmitting the same HARQ PSDU or considering it lost.

IV. SIMULATION RESULTS AND DISCUSSION

A. Parameters

The downlink of WiMAX was selected to evaluate the performance of the HARQ mechanism. The physical layer specifications used in the simulations are presented in Tables I and II.

In order to perform more realistic simulations a time-varying multipath channel has been considered. The chosen channel model is the Spatial Channel Model Extended (SCME), which generates channel coefficients based on 3GPP channel model specifications [13]. The WINNER SCME [14] is a set of Matlab® scripts used to provide samples of a multipath channel according to the 3GPP Spatial Channel Model. The parameters settings are presented in Table III and were used in all simulations, unless indicated otherwise.

For the purpose of channel estimation, a least squares channel estimator was used, as described in [15] and references therein. In the legends, it is noted as LS CSI (lest squares channel state information), opposed to perfect CSI. The algorithm used for channel decoding is the Soft Output Viterbi Algorithm (SOVA).

The investigated HARQ mechanism is the incremental redundancy (IR). In the implemented retransmission mechanism, a given subpacket is retransmitted at most four more times. If in these five initial attempts the receiver has not properly decoded the packet,

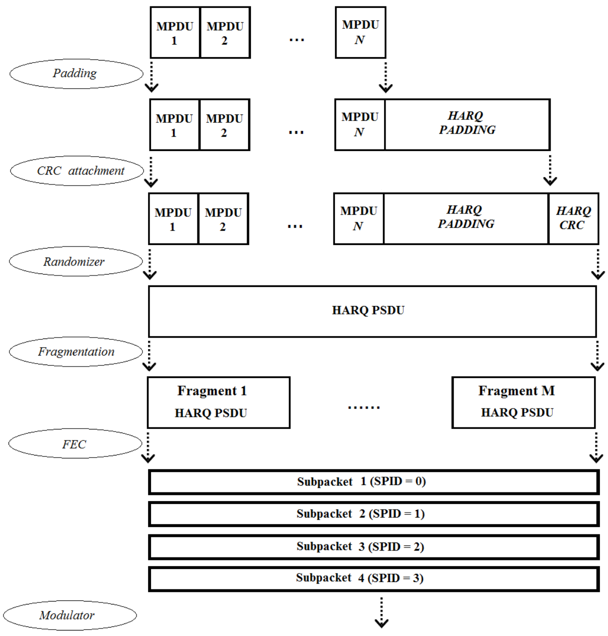


Fig. 1: HARQ procedures as defined in WiMAX (IEEE 802.16e) standard.

TABLE I: Physical Layer Specifications for the Purpose of Simulation.

Parameter	Value
Bandwidth	20 MHz
Number of subcarriers	2048
Cyclic prefix length	1/8
Permutation mode	DL PUSC
OFDM symbols per frame	18
Channel Coding	Convolutional code (as defined in [12])
CRC	ITU-T x25
Channel Model	WINNER's SCME
Channel Estimation method	LS
Channel decoder	SOVA
HARQ method	IR

the memory is cleared and the block is retransmitted at most five more times (note that the previous five attempts, before the memory cleaning, do not contribute to the decoding). If after all these transmission attempts the block is still received with errors, the packets are simply discarded.

It is important to remark that for each modulation and coding rate, different block sizes were considered. Their size is indicated as a function of the number of allocated slots (noted as *AS*) used for transmitting the given HARQ PSDU.

B. Performance Results

Fig. 2 shows that there is a considerable difference on the performance of HARQ scheme when imperfect channel information is available at the receiver (due to the limitations of channel estimation). All modulation schemes experience loss in the achieved throughput. For low values of E_b/N_0, this loss can be superior to 4 Mbps, depending on the modulation order. One can realize that this throughput loss must be taken into account when analyzing or deploying the system since one tends to transmit with lower values of SNR when using HARQ, and channel estimation losses are higher in this case. In the high SNR regime, the throughput loss may be inferior to 1 Mbps due to the better channel estimation. We also point out that values of E_b/N_o superior to 14 dB, it is preferred to employ 64QAM instead of 16QAM, once it is known that when operating in low SNR regime, higher-order modulations present mean bit error rates higher than those exhibited by lower-order modulations.

TABLE II: Code Rates.

Modulation	Code Rate (r)
QPSK	1/2, 3/4
16QAM	1/2, 3/4
64QAM	1/2, 2/3, 5/6

TABLE III: WINNER's SCME Parameters.

Parameters	Value
Carrier frequency	2.0 GHz
Mobile speed	10.8 m/s
Number of antennas at Base Station	1
Number of antennas at Mobile Station	1
Scenario	Suburban Macro
Number of paths	12

Fig. 3 shows the effect of the code rate on HARQ. It is interesting to note that when perfect CSI is available, a higher code rate (such as 3/4) might be used. Since there are more information bits per transmitted symbol, the throughput will be higher. When imperfect CSI is available, the situation is more complex, as shown by the behavior of 16QAM modulation.

Fig. 4 illustrates the impact of the size of HARQ PSDU on the performance of HARQ. For values of E_b/N_o ratio above 10 dB, changing the PSDU size from 4 AS to 40 AS can lead to a gain of about 1 Mbps in the throughput. Firstly, because this procedure reduces the information loss caused by the CRC attachment, and secondly because larger block sizes lead to more robust performance of the codes. Once again the effect of imperfect CSI can be observed.

In order to quantify the benefit of HARQ, we also use as a performance metric the average number of retransmissions required to decode a FEC block without errors. This is considered in Fig. 5 for a block size of 4 AS and in Fig. 6 for a block size of 40 AS. For a value of E_b/N_o of 14 dB, there are almost no retransmissions and a higher code rate is preferable, since it implies in higher information

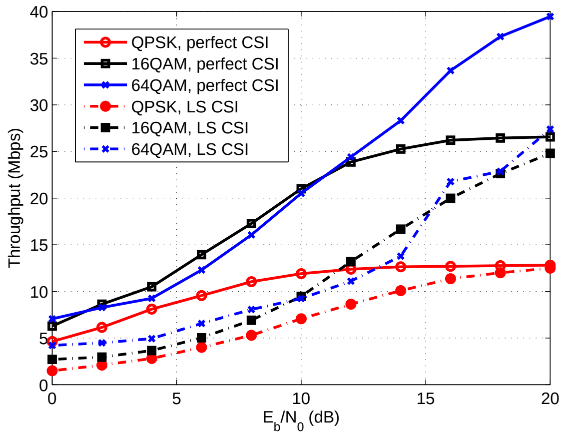


Fig. 2: Throughput of WiMAX using a code rate r = 1/2 and HARQ PSDU size of 4 AS.

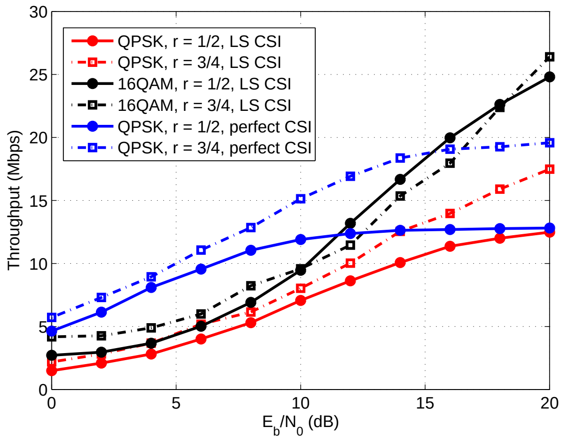


Fig. 3: Throughput of WiMAX for QPSK and modulations and HARQ PSDU size of 4 AS.

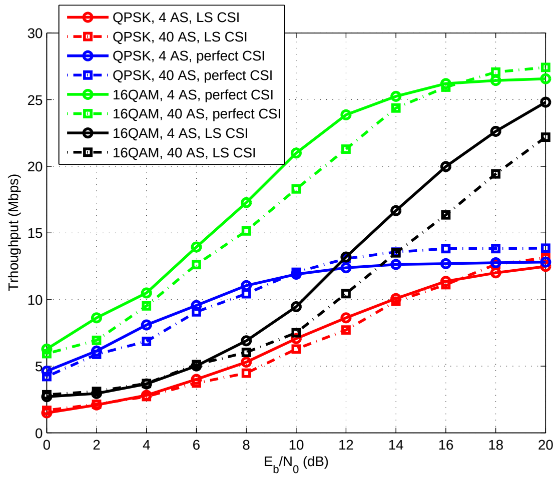


Fig. 4: Throughput of WiMAX for QPSK and 16 QAM using a code rate r = 1/2 and HARQ PSDU size of 4 AS and 40 AS.

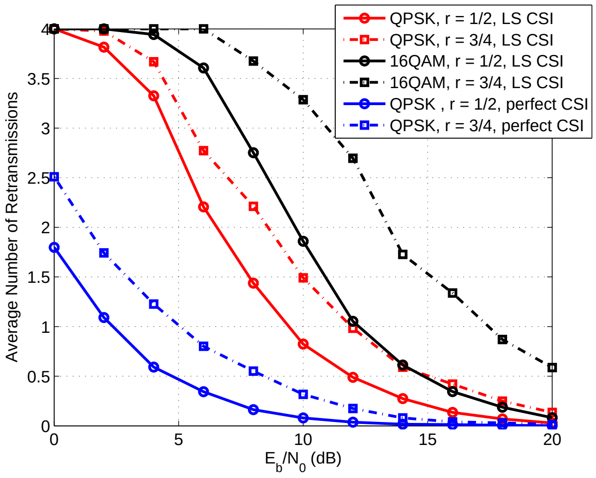


Fig. 5: Average number of retransmissions for QPSK and 16QAM and HARQ PSDU size of 4 AS.

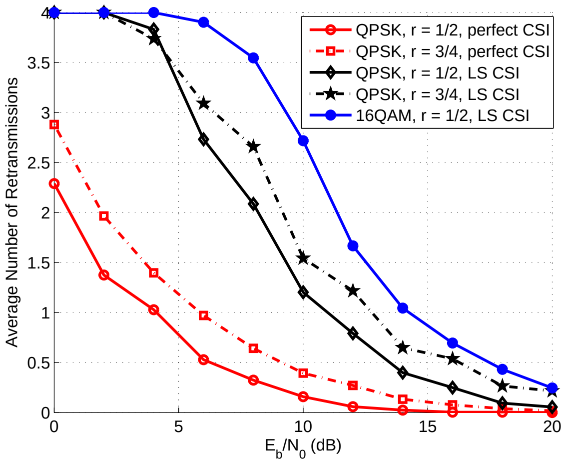


Fig. 6: Average number of retransmissions for QPSK and 16QAM and HARQ PSDU size of 40 AS.

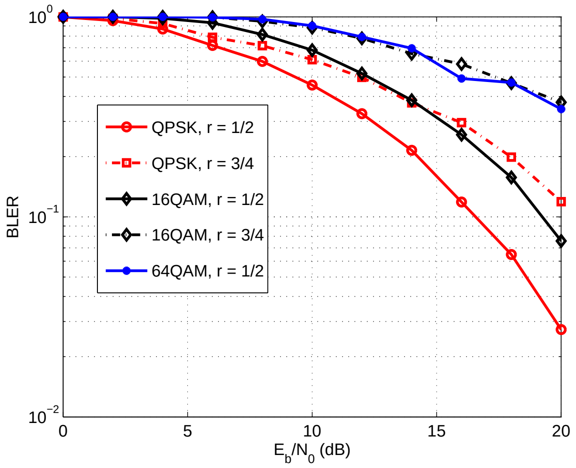
bits per transmitted symbol. At high SNR, there is no apparent benefit from HARQ, since most of the FEC blocks are decoded without error at the first transmission. One can also remark that the mean number of retransmissions is lightly lower when transmitting with a block size of 40 AS due to the robustness of the code for larger input blocks.

In Fig. 7, we show the mean block error rate (BLER) of the system. Although not directly related to HARQ, the figure is useful to understand the inherent limitations of the system and it can be used as a benchmark to the previous analysis. For instance, at $E_b/N_o = 0$ dB, not only the noise level is high, but also the reliability of the channel estimate is quite poor. This reflects in a high BLER, a greater number of retransmissions and consequently lower throughput, as shown in the previous figures. On the other hand, at $E_b/N_o = 20$ dB, the reliability of the channel estimate is good, and the performance of HARQ under perfect CSI and LS CSI exhibits a tendency to converge to the same value.

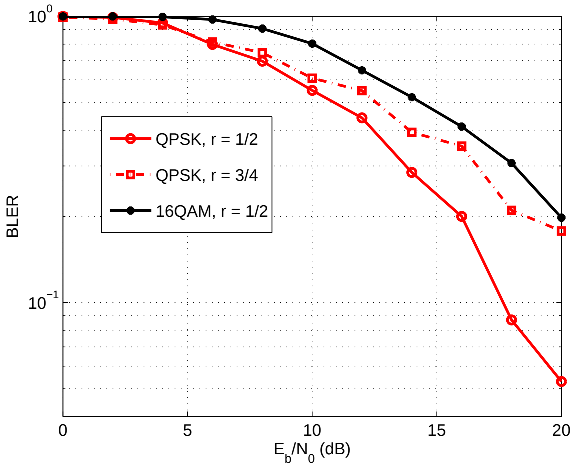
Finally we assess in Fig. 8 the performance of several combinations of modulation, coding rate and HARQ PSDU block size over an additive white Gaussian noise (AWGN) channel. This is done for the sake of comparison between the best performance that can be achieved and the performance of the system under a multipath channel, since the Shannon capacity is used as a measure of the efficiency of the system and in an AWNG channel the receiver does not need to mitigate any impairment or adverse effect of the channel. Although a real-word wireless channel is not AWGN in nature, the results can be used, for instance, to evaluate the performance relative to the Shannon capacity and determine the thresholds for link adaptation schemes. It is worthwhile to remark that the combination of 16QAM modulation and a code rate of 3/4 offers higher throughput than the 64QAM modulation with a code rate of 1/2. There is also a gap of approximately 6 to 10 dB between the Shannon theoretical bound and the maximum achievable throughput. Here the importance of the HARQ PSDU size on the performance of the HARQ scheme is once again noticeable, as well as the SNR values that can be used to switch between the different types of modulation, coding rate and PSDU block size.

V. CONCLUSION

In this paper, we have presented several simulation results regarding the performance of the incremental redundancy HARQ used on



(a) 4 AS.



(b) 40 AS.

Fig. 7: Block error rate for QPSK and 16QAM modulation for different code rates and HARQ PSDU block sizes of (a) 4 AS and (b) 40 AS under LS CSI.

WiMAX standard considering realistic channel estimation algorithms. We focused more specifically on the least squares estimator. It is known that channel estimation is a significant part of the operation of any real receiver and it has a significant impact on the link performance, as the results have shown.

We have compared the link throughput under two scenarios: one in which the CSI is provided by the LS estimator and the other in which the receiver is assumed to have perfect channel knowledge. In both of them we considered several combinations of modulation schemes, code rate and information block size used for transmission, as well as several performance metrics, such as the average number of retransmissions and BLER. As expected, the performance of HARQ was severely degraded when imperfect channel information is available, mostly in the low SNR regime, which is the regime we tend to transmit when implementing HARQ. This happens because the reliability of channel estimation is also lower at this operation point, having a very large impact on performance.

As a suggestion for further work, the proposal of HARQ combining algorithms that take into account the presence of unreliable information about the channel (such as the one that is present at receiver when channel estimation is performed under low SNR regimes) may be considered. We believe that this may lead to a potential performance gain, reducing the loss in the throughput.

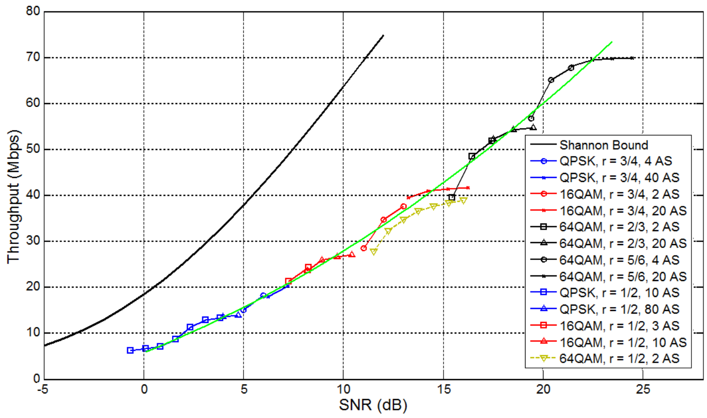


Fig. 8: Shannon capacity and WiMAX throughput over AWGN channel.

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