



Link Performance Model for Multihop WiMax OFDMA Systems

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Abstract: A two-phased approach is proposed to estimate the overall multi-hop WiMax system performance. The proposed methodology is generic and can embrace various multi transmit multi receive techniques along with different possible (H)ARQ mechanisms. Advanced modulation and coding sub-carrier mapping is assumed for static and low mobility links to allow operation of adaptive techniques such as dynamic band allocation and beam-forming. PUSC sub-carrier mapping is assumed to be used for dynamic and high mobility links. In order to illustrate our methodology, the overall PER performance of a two-hop system with eigen beam-forming in first hop and either Alamouti or Golden codes in the second hop has been estimated. The results are based on the combination of the two link performance models, i.e., actual value interface for the first hop and average value interface for the second hop.

Keywords: WiMax, OFDMA, multi-hop, link performance model, space-time code, beam-forming.

1. Introduction

Worldwide interoperability for Microwave access (WiMax) is a wireless communication technology designed to provide wireless transmission over long distances in a variety of ways, from point-to-point fixed wireless links to full mobile cellular types of access. This technology is based on the IEEE 802.16 standard [1], i.e., wireless Metropolitan Area Network (MAN) standard, and since its introduction in 2001 it has evolved into several versions, namely 'a', 'd' referred as the fixed WiMax, and 'e' referred as the mobile WiMax. WiMax is a technology that enables the delivery of the last mile wireless broadband access, and in the meantime offering an alternative to wired access networks, such as fibre optic or digital subscriber line links. The 802.16e standard defines several combinations of modulation, channel coding method, and rate that allows to reach a given data rate or a certain level of robustness according to the propagation environment. In this paper, we consider the Wireless MAN orthogonal frequency division multiple access (OFDMA) air interface for its potential in efficient usage of the radio spectrum as well as its support of different multiple antenna transmission techniques.

Multihop and cooperative relaying is a promising enabler for providing high data rate services to far and shadowed users. A Multihop Cellular Network (MCN) usually benefits from a number of fixed relay stations that forward far users' data in both Downlink (DL) and Uplink (UL) directions. Operation of WiMax systems over an MCN will be covered in 802.16j standard [3]. Advanced adaptive and non-adaptive multi antenna techniques combined with a right selection of WiMax subcarrier mapping and multi-hop relaying improve the system reliability and the spectrum efficiency. A huge number of combinations arise when transmission configuration is allowed to change on per hop basis. An efficient and simple evaluation methodology is then required to reliably estimate the overall

multihop route end-to-end performance for any combination of the selected transmit configurations and under different channel conditions. Here we address this need and propose a two phased evaluation approach to estimate important performance metrics for a multihop route.

2. Wireless MAN-OFDMA Air Interface

2.1 General View

The wireless MAN-OFDMA air interface is designed for Non-Line of Sight (NLOS) operation in the frequency bands between 2-5 and 11 GHz, and using bandwidth sizes from a minimum of 1.25 MHz up to 28 MHz. The orthogonal frequency division multiplexing (OFDM) modulation is accommodated over the bandwidth using four possible fast Fourier transform (FFT) sizes of 128, 512, 1024, and 2048 and four possible guard time overhead lengths. Moreover, the standard provides flexible mapping of users' data into subcarriers of the OFDM signal. The two dimensional radio resources composed of OFDM subcarriers, i.e., frequency domain, and their continuation along the time domain, endows the system with flexibility in efficient allocation of system spectrum resources to different users.

Two potential types of the provisioned subcarrier mappings are the Partial Usage of Sub-Carriers (PUSC), and the subcarrier mapping for Advanced Modulation and Coding (AMC). PUSC is a good candidate for highly mobile condition where provision of transmit channel knowledge with an appropriate level of quality is not possible and the best that can be done is to transmit users signals over non-adjacent subcarriers with the hope of achieving frequency domain diversity. On the other hand the AMC subcarrier mapping uses adjacent subcarriers and is suitable for low mobility conditions where transmit channel knowledge can be obtained reliably and with negligible cost. This knowledge can be efficiently utilised by dynamic allocation of AMC bands to users (DBA), followed by properly adjusted power, multi antenna transmission mode, coding and modulation for each user's traffic. Thus, a two zone frame structure composed of PUSC and AMC zones allows an efficient exploitation of users' conditions for a communication scenario composed of users with different mobilities.

The two-zone frame structure can also be utilised in relay-augmented communication systems where multihop and cooperative transmission techniques can be potentially exploited. Assuming a two-hop relaying where the link between the base and the relay stations is almost static and the link between the relay station and the user is dynamic, it would be wise to combine the AMC and PUSC subcarrier mappings in conjunction with DBA and adaptive techniques over the static link and diversity coding techniques over the dynamic link.

2.2 Motivation

Considering a multi-hop scenario, which is composed of three types of nodes, namely, Base Stations (BSs), Relay Stations (RSs), and Subscriber Stations (SSs), as depicted in Figure 1, a huge number of transmission mode combinations could arise. The transmission mode should be properly adjusted based on the channel conditions of the different links. Advanced techniques such as eigen Beam-Forming (BF), Spatial Division Multiple Access (SDMA), spatial multiplexing, and space-time diversity coding should be used in conjunction with PUSC and AMC subcarrier mappings according to the multi antenna transmission/reception capability and the mobility condition of each node. The Performance evaluation of these techniques for all possible adaptive, non-adaptive techniques, and channel conditions is a very daunting task. Therefore, appropriate and simple evaluation approaches are required to model the effect of the multihop and cooperative relaying performance. Here, we only focus on multi-hop relaying and describe a two-phase approach

to effectively estimate the overall performance. In the first phase, the performance of each single constituting hop is evaluated, and in the second phase, the final performance is computed by an appropriate combining of the constituting hops' performance metrics.

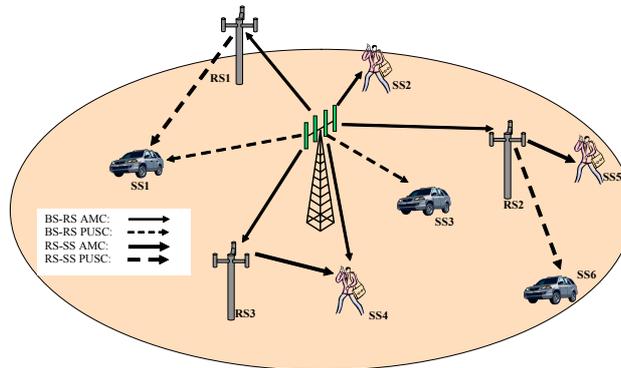


Figure 1: Multi-Hop Communication Scenario

3. Generic Equivalent Single Input Single Output (SISO) System Model for Link Performance Evaluation

A generic link-level system model for the wireless MAN-OFDMA air interface, considering multi-transmit multi-receive (MTMR) processing, multi-user configuration, and DBA, is depicted in Figure 2. Complex encoded and modulated symbols (usually M -QAM or M -PSK) from single or multi-user traffic are fed into an MTMR transmit processing. This processing is usually linear and can use transmit channel state information if operating in an adaptive mode. Thereafter, the MTMR processed data are mapped to one or several AMC bands based on dynamic decisions of a band allocation algorithm. If MTMR processing is operating in adaptive mode, then both the MTMR transmit processing and the DBA blocks should be jointly controlled. At the receiver side, in one of the intended receivers (receiver j in Figure 2) the data is extracted from the allocated band and further processed by an MTMR receive (Rx) processing.

The output would be a distorted version of the intended user (user j) complex data. This data should be further processed by the corresponding de-modulation and decoding stages. Usually the MTMR Rx processing is also linear, even though non-linear ones like maximum likelihood, maximum a posteriori, and Sphere Detection (SD) are also possible. Furthermore, turbo processing principle is also applicable that will couple MTMR processing and de-modulation and decoding stages together. Considering that linear detectors are widely used in practice, we assume in the sequel that the employed MTMR Rx processing is linear. Thus, an equivalent single user SISO channel model can be considered that greatly simplify the performance modelling. Performance modelling for non-linear detectors will require further investigation but it is not in the scope of this paper.

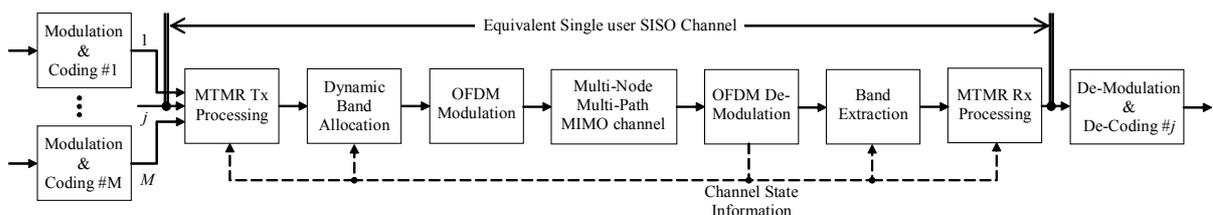


Figure 2: A Generic Model for Dynamic Band Allocation and Single or Multi-User MTMR Processing

3.1 Example: Eigen BF

Here as an example the equivalent SISO channel model is derived when eigen BF technique is employed. Let us assume a multi-input multi-output (MIMO) channel matrix \mathbf{H} realised for an AMC band, eigen BF is applied by eigen or singular value decomposition of $\mathbf{H}=\mathbf{U}\mathbf{D}\mathbf{V}^h$, where \mathbf{U} and \mathbf{V} are unitary matrices and \mathbf{D} is a matrix with non-zero elements in the main diagonal and such that all the non-zero components are positive. The MTMR transmit processing can be represented by $\mathbf{V}\mathbf{\Lambda}\mathbf{x}$ where \mathbf{x} is a column vector containing complex data symbols, $\mathbf{\Lambda}$ is a diagonal matrix with non-negative diagonal elements and applies power allocation. Power allocation could be based on water filling or any practical scheme, and here we assume a simple SNR balancing approach. At the receiver, the received vector $\mathbf{r} = \mathbf{H}\mathbf{V}\mathbf{\Lambda}\mathbf{x}+\mathbf{n}$ is linearly processed by $\mathbf{y}=\mathbf{U}^h\mathbf{r}=\mathbf{D}\mathbf{\Lambda}\mathbf{x}+ \mathbf{U}^h\mathbf{n}= \mathbf{D}\mathbf{\Lambda}\mathbf{x}+ \boldsymbol{\eta}$. The matrix \mathbf{U} being unitary, $\boldsymbol{\eta}$ has an identical power and distribution as \mathbf{n} . Thus, an equivalent SISO channel model expressed as $y_k = \alpha_k x_k + \eta_k$, where α_k are the diagonal components of the $\mathbf{D}\mathbf{\Lambda}$, is obtained.

4. Multi-Hop Systems Evaluation Methodology

4.1 Single-Hop Evaluation Phase

In this phase a sub-scenario of point-to-point, point-to-multipoint, and multipoint-to-point communication with different possible combinations of BS, RSs, and SSs is setup, and performance of all the single hops are evaluated. For instance, let us assume a multipoint-to-point communication where a number of SSs and RSs are carrying out a time-frequency simultaneous UL transmissions towards a BS. Assuming that the BS is equipped with multiple receive antennae, the BS carries out joint detection to separate all the transmitted signals. The performance of each SS-to-BS and RS-to-BS single hop is affected by this multipoint-to-point communication, and the performance of each single hop should be evaluated in conjunction with the exploited BS's joint detector.

In low mobility propagation condition, the Packet Error Rate (PER) of a transmitted packet depends on the instantaneous state of the channel when the packet was transmitted. Actual Value Interfacing (ACVI) [1], which is a well-known link performance estimation technique, should be used to model the link performance in this type of condition. For an OFDM or OFDMA system, a wideband channel state could be expressed in terms of the realised SNRs on each subcarrier. An ACVI maps the set of realised SNRs into one value known as the effective SNR. The important property of this mapping is the compression of a large dimensional channel state into an effective metric such that different channel states with the same effective metric render almost the same performance, as follows

$$\boldsymbol{\theta}_{eff} = M_s(\boldsymbol{\theta}), PER(\boldsymbol{\theta}) \approx f_s(\boldsymbol{\theta}_{eff}), \quad (1)$$

where $\boldsymbol{\theta}$ represents the large dimensional channel state vector, and the subscript S denotes all the modulation and coding settings of the link. The function $M_s(\cdot)$ maps $\boldsymbol{\theta}$ to the effective metric $\boldsymbol{\theta}_{eff}$, and $f_s(\boldsymbol{\theta}_{eff})$ provides an estimation of the PER for the given effective metric $\boldsymbol{\theta}_{eff}$. Among the effective metrics introduced in [1], Exponential Effective SINR Metric (EESM), and Mutual Information Effective SINR metric (MIESM) can be used for each hop evaluation. ACVI can be extended to provide an estimation of PER when a (hybrid) automatic request for repeat ((H)ARQ) process is attached to a link. For ARQ operation, the PER of each transmission can be estimated using the same method as for a traditional single transmission. For a HARQ process, the final PER is a function of all the observed channel states: $\boldsymbol{\theta}_j$, for $j=1, \dots, n$ where subscript j denotes the transmission number of a data packet and n is the number of HARQ transmissions carried out. In this case, a

number of effective mappings, each computed for a fixed number of HARQ data packet transmissions, can be provided as

$$\theta_{eff}^n = M_S^n(\theta_1, \theta_2, \dots, \theta_n), PER(\theta_1, \theta_2, \dots, \theta_n) \approx f_S^n(\theta_{eff}^n), \text{ for } n = 1, \dots, N_T, \quad (2)$$

where N_T is maximum allowed number of HARQ transmissions, $M_S^n(\cdot)$ calculates the effective metric θ_{eff}^n for n number of HARQ packet transmissions, and $f_S^n(\theta_{eff}^n)$ provides the corresponding estimated PER.

In high-mobility propagation condition, the PER of the transmitted packet is no more dependent of the observed channel states. On average all the typical channel conditions are likely to happen during the transmission. In this case, the straightforward Average Value Interface (AVVI) technique can be applied to model the link performance.

4.2 Multi-Hop Evaluation Phase

The final performance is computed by combining the performance metrics obtained for each single hop. Different approaches should be considered to achieve a reliable estimation of the final performance, depending on the possibility of activation of (H)ARQ and on the dynamics of the constituting hops.

The key performance metrics are throughput, latency, last transmitted PER and bit error rate (BER) when (H)ARQ is implemented at RSs. In this case each single hop can be associated with an (H)ARQ process. Generally, there might be situations where some of the hops are not equipped with an (H)ARQ process. However, a link (hop) without (H)ARQ can be associated with a trivial (H)ARQ process with maximum transmission equal to 1. Figure 3 depicts a generic multihop chain with corresponding associated (H)ARQ processes. In this figure T_j , L_j , PER_j , and BER_j denote the throughput, the latency, and the last transmitted PER and BER of the j th hop, respectively. The performance metrics T_j , L_j can be treated as random variables and their distributions can be measured by physical layer simulations of the corresponding hop. Usually mean values of these parameters are large enough for higher layer analysis. However, physical layer simulators can provide extra measures such as minimum and maximum values versus SNR, and their histograms can also be provided. Here these two parameters are assumed to represent the corresponding mean values. Non-zero last transmitted PER and BER are due to persistent severe channel conditions such that after all the allowed retransmissions, the system is still not able to recover the data packet. Also undetected error events of the CRC checking cause erroneous received packets. Depending on the relative mobility of the nodes, different hops might have different channel dynamics. As explained in the previous section, one of the two average and actual value interfacing should be used as link quality models for high and low mobility conditions, respectively. The overall multi-hop link quality can be evaluated by combining the constituting hops' link quality measures. Figure 4(a) provides a top level flowchart describing how the two actual value and average value interfaces of the constituting hops should be combined to produce an estimation of the HARQ measures for the entire multi-hop link.

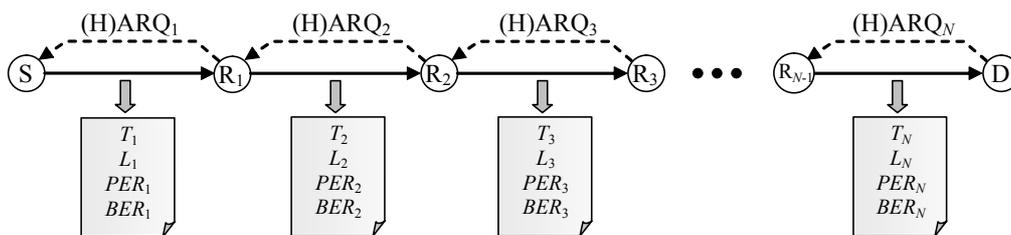


Figure 3: A Multi-Hop Chain With an (H)ARQ Attached to Each Constituting Hop

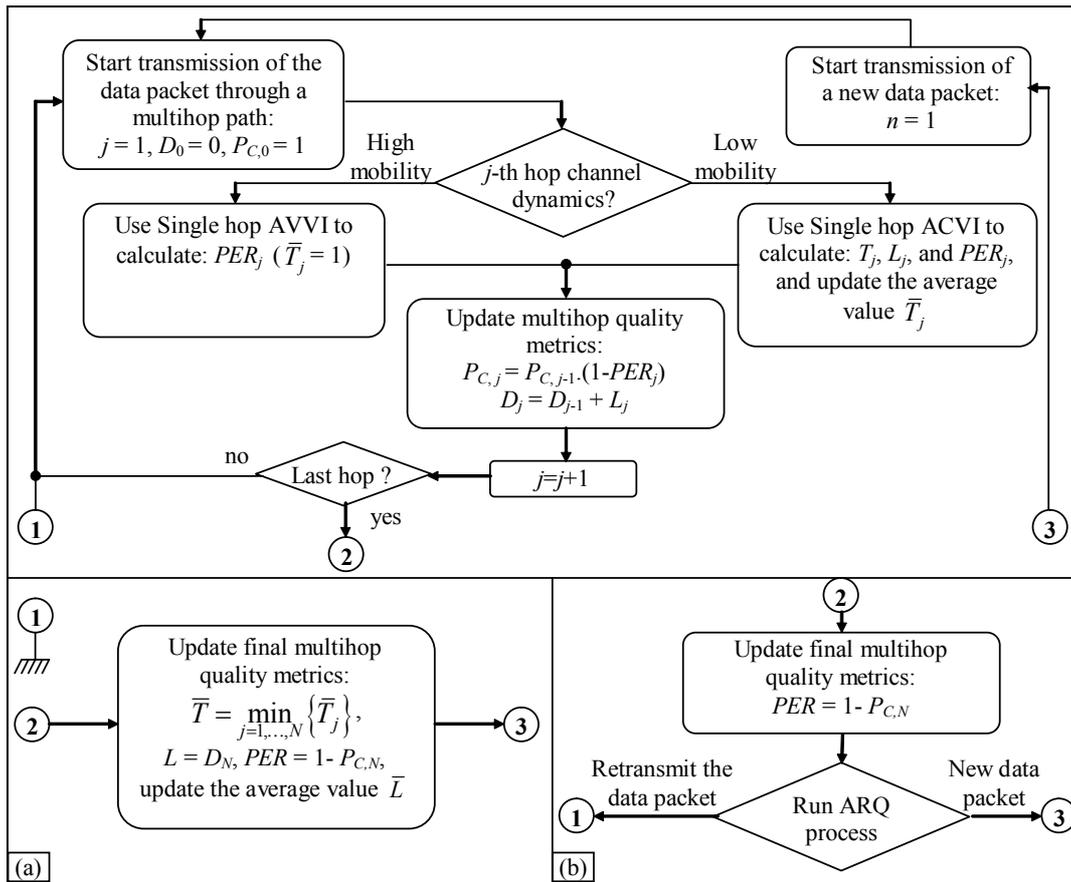


Figure 4: Multihop Link Quality Evaluation, (a) if Some or All of the Hops Have Associated HARQ Processes, (b) if Only One ARQ Process is Associated to the Entire Multi-Hop Route

No (H)ARQ at Relay Nodes: In this case only one (H)ARQ is attached to the entire multihop link. (H)ARQ process should be implemented separately for the entire multihop route as non of the single hop physical layer simulator can run the (H)ARQ process alone. This approach maintains the accuracy of the ARQ process, but as HARQ tries to effectively combine the information received via several transmissions of a packet, it only provides an approximation. Similar to the previous case, one of the two actual and average value interfaces should be used depending on the dynamics of each constituting link. Figure 4(b) provides a top level flowchart describing the multihop link quality evaluation with one ARQ process controlling the entire multihop route.

5. Simulation Results: WiMax Multi-Hop Performance Evaluation

In this section we present the aggregate performance result of a MIMO WiMax system transmitting between the BS to SS via a RS. The performance of each link is obtained separately and then the overall performance is estimated using the multihop evaluation methodology presented in Section 4. Two antenna elements are assumed for each node. The RS node is assumed to be fixed and the BS-RS link is modelled by an Urban Outdoor High-to-Medium (UOHM) channel, and the RS-SS link is modelled by an Urban Outdoor Medium-to-Low (UOML) channel for high mobility (0-120kkm) [6]. Perfect channel estimation is assumed for all the results. The simulations are based on the following WiMax settings: the frequency band is 3.4 – 3.7 GHz, the bandwidth is 5 MHz, the FFT size is 512, the sampling factor is 28/25, the guard to useful time ratio is 1/8, the subcarrier mappings are AMC or PUSC with all sub-channels, the FEC code is a half-rate CCTB, and the modulation is a QPSK. The results are obtained for the car scenario of the Fireworks channel model [5]. The overall PER performance is estimated for two-hop relaying over

BS-RS and then RS-SS links. Eigen BF along with AMC subcarrier mapping is applied for the first hop, while the second hop resort to space-time coding and PUSC subcarrier mapping. Alamouti and Golden code (GC) [9] are considered as two options for space-time coding.

Actual Value Interface Setup: Using spatial multiplexing, different 2x2 MIMO channel realisations based on the UOHM channel model are generated and simulation is carried out under zero mobility (essentially the proposed channel model itself is zero mobility) and MMSE receiver is used to detect data symbols. Two non-adjacent AMC bands (bands 0 and 20) are used for data transmission. Figure 5 provide the PER simulation results for different channel realisations in the average SNR domain as well as the effective SNR domain. Only results for EESM are presented. MIESM provided similar performance, and both the mappings provided acceptable mapped PER curves close to the AWGN performance.

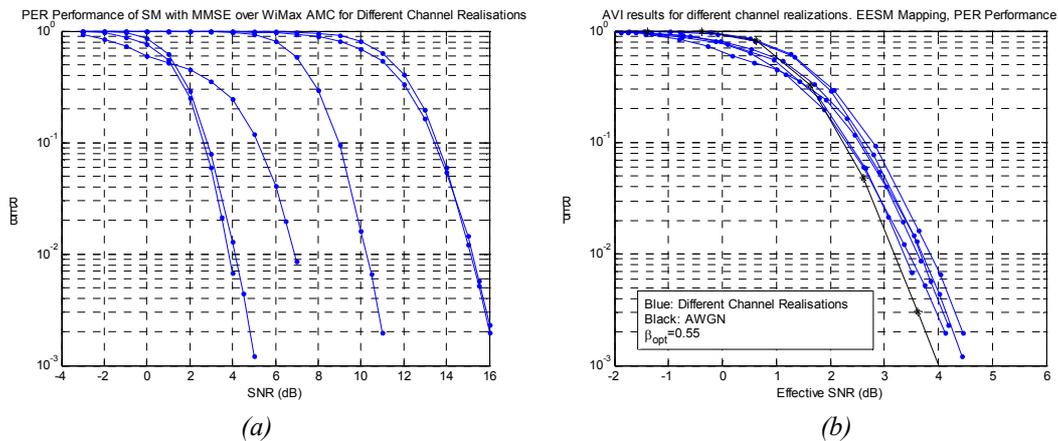


Figure 5 PER Performance for Spatial Multiplexing, 2x2 MIMO Channel, MMSE Receiver, Under Zero Mobility and Different Channel Realisations (a) PER Versus Average SNR, (b) EESM with $\beta=0.55$.

Figure 6 provides the overall PER performance of the considered two-hop relayed WiMax system. Figure 6a is related to the Alamouti code [8] in the second hop, and Figure 6b provides the performance when the Alamouti code is replaced by the Golden Code (GC) [9] with list-SD detection [10]. The results for the first link, i.e., BS-RS DL, have been obtained by generating one channel realization of the channel depicted in Figure 5. Please note that GC twice spectrum efficient that Alamouti scheme.

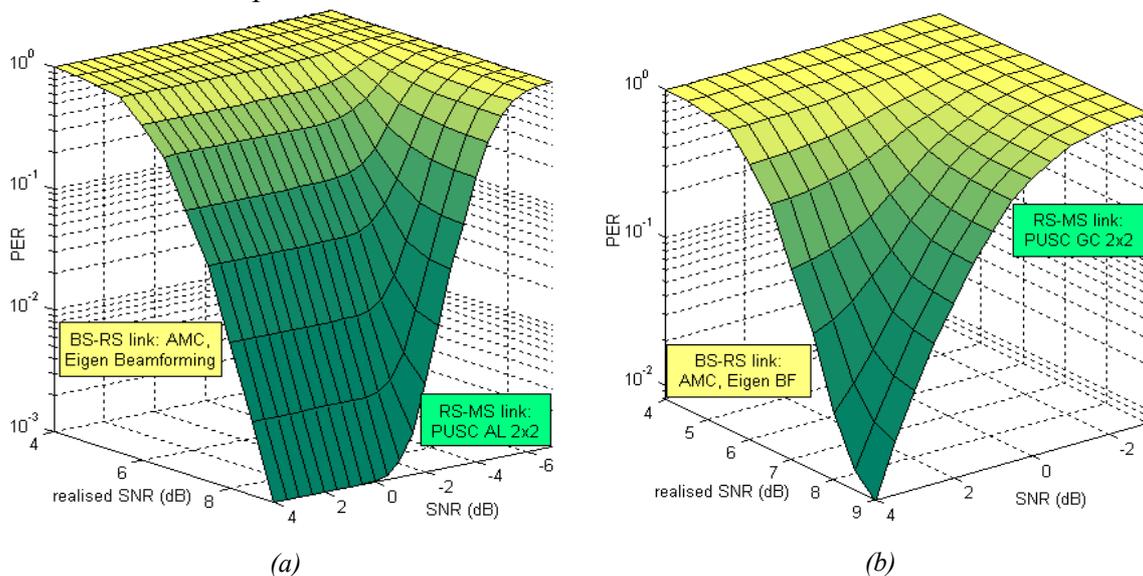


Figure 6 PER Performance Combination for the 2x2 MIMO Multi-Hop WiMax system, DL link, Car Scenario, BS-RS Link : AMC/Beamforming, RS-MS link : (a) PUSC/Alamouti Scheme / (b) PUSC/Golden Code

6. Conclusions

WiMax OFDMA system needs to properly exploit different channel conditions of the users' constituting multi-hop links through right selection of AMC and PUSC sub-carrier mappings along with appropriate adaptive and non-adaptive multi antenna techniques when deployed over relay-augmented cellular system. Due to the large number of possible combinations with respect to users' mobility, channel conditions, antenna configuration, and established multi-hop routes, an efficient and simple performance abstraction is required. A two-phased approach is proposed in this paper explaining how to combine single hop performance metrics and to obtain an estimation of the overall multi-hop system performance. The proposed methodology is generic and can embrace different MTMR techniques along with different possible (H)ARQ mechanisms. As an example, an overall PER performance of a two-hop system using eigen BF in the first hop and either Alamouti or GC in the second hop has been estimated. Further investigation will be required to extend and validate the proposed approach when non-linear detection techniques are engaged.

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