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**Link Adaptive and QoS Provisioning Cooperative ARQ - Applications to
Relay Assisted Land Mobile Satellite Communications**

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Link Adaptive and QoS Provisioning Cooperative ARQ - Applications to Relay Assisted Land Mobile Satellite Communications^{*}

Morteza Mardani, *Student Member, IEEE*, Jalil Seifali Harsini, Farshad Lahouti, *Member, IEEE*, and Behrooz Eliasi

Abstract

In a cooperative relay network, a relay node (R) may facilitate data transmission to the destination node (D), when the latter is unable to decode the source node (S) data correctly. This paper considers such a system model and presents a cross-layer approach to jointly design adaptive modulation and coding (AMC) at the physical layer and cooperative truncated automatic repeat request (C-ARQ) protocol at the data link layer for quality of service (QoS) constrained applications. The average spectral efficiency and packet loss rate of the joint C-ARQ and AMC scheme are first derived in closed-form. Aiming at maximizing the system spectral efficiency, AMC schemes for S-D and R-D links are optimized while a prescribed packet loss rate constraint is satisfied. As an interesting application, joint link adaptation and blockage mitigation in land mobile satellite communications (LMSC) with temporally correlated channels is then investigated. In LMSC, the S node data can be delivered to the D node when the S-D is in the outage, thereby provisioning the QoS requirements. For applications without instantaneous feedback, an optimized rate selection scheme based on the channel statistics is also devised. Detailed and insightful numerical results are presented, which indicate the superior performance

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of the proposed joint AMC and C-ARQ schemes over their optimized joint AMC and traditional ARQ counterparts.

Key Words: Cooperative ARQ, adaptive modulation and coding, quality of service, cross-layer design, land mobile satellite communications.

I. INTRODUCTION

Recently, cooperative communication has attracted substantial research attention as a promising technique to achieve diversity gain in wireless networks. In particular, cooperative automatic repeat request (C-ARQ) is a link-level protocol which exploits the spatial diversity of the relay channel. It outperforms a traditional automatic repeat request (T-ARQ) scheme, particularly when the source to destination (S-D) channel is subject to a high temporal correlation [1][2]. The main idea behind this protocol is to jointly exploit the benefits of two relaying protocols: (i) the incremental decode and forward (DF) relaying protocol, which prescribes a retransmission via relay only when the destination decodes the source data in error [3], and (ii) the selection DF protocol, which verifies that the data is received correctly at the relay, prior to a relay to destination (R-D) transmission [3].

There are several studies on the topic of C-ARQ over a relay channel, e.g., [1] [2] [4]-[6]. Utilizing a distributed space-time coded retransmission protocol, in [3] a truncated C-ARQ is proposed, which exploits adaptive cooperative diversity, where the relay nodes are selected using a cyclic redundancy check (CRC) code. In [1], for several C-ARQ protocols, the link layer performance including both throughput and packet loss rate (PLR), is studied over slow fading channels. Their results illustrate that the C-ARQ protocol compared to the T-ARQ, achieves better performance if the average SNR of the relay to destination channel is better than a given threshold. In [5], closed form expressions for the throughput performance of several cooperative relaying protocols are presented. They used a simulation setup to investigate the effect of

optimized rate selection based on channel statistics (average SNR) on the system throughput. In [2], a stop and wait C-ARQ protocol is developed and analyzed for improved throughput and packet delay performance over time-correlated fading channels. The delay performance of a set of C-ARQ protocols is also investigated in [6], where data frame arrival at the source node is modeled by a Poisson process. In [32], the energy efficiency of the C-ARQ protocols is studied when both the energy consumption due transmission and the circuitry are taken into account. The energy per bit and transmission rate are jointly optimized to minimize the average consumed energy per packet, while the outage constraint is satisfied. However, the optimization variables are set based on channel statistics for the whole connection, and the outage event is considered as the only source of error. The research reported in [7] verifies that utilizing a cooperative retransmission strategy, compared to a T-ARQ, reduces both the system load and the packet delay in mobile satellite communication systems suffering from channel blockage effects.

Efficient and reliable communications over wireless (relay) networks is challenging given the time varying nature of wireless links and especially when stringent qualities of service (QoS) requirements are to be provisioned. Adaptive modulation and coding (AMC) is known as a powerful technique to enhance the system spectral efficiency for communications over wireless fading channels [8][9]. In fact, for the same reason, AMC schemes are already included in wireless communication standards such as HIPERLAN/2, IEEE 802.11 and IEEE 802.16e. The AMC is also of great interest in satellite communications and is adopted in the DVB-S2 standard [10]-[12]. The idea of applying AMC to a wireless relay network is investigated in [13] and [14].

In [13], a discrete rate and power adaptation policy is proposed for the fixed DF relay channel. Transmission during outage is counted as the only source of error as capacity achieving codes are assumed that resolve errors due to channel noise. In [14], an OFDM based wireless

relay network is considered and aiming at optimizing the end-to-end instantaneous throughput, a joint relaying scheme (without ARQ) and AMC mode selection algorithm is proposed, where the solutions are provided in the form of lookup tables.

As elaborated above, in the literature, both the C-ARQ protocol and AMC over relay channels are separately investigated. However, to the best of our knowledge, the problem of designing discrete-rate AMC schemes in conjunction with a C-ARQ protocol for QoS constrained applications in wireless relay networks has not been addressed so far. This will be promising especially in land mobile satellite communication (LMSC) systems, where the communication channel experiences both blockage and multipath fading effects.

The main contribution of this paper is to quantify the potential performance gain achieved by the joint design of discrete-rate AMC with C-ARQ (hereinafter referred to as adaptive rate C-ARQ) for QoS constrained applications over wireless networks. Here, the term QoS corresponds to delay and packet loss rate requirements. To this end, we take a cross-layer design approach. We first derive an exact closed-form expression for the average spectral efficiency (SE) and packet loss rate of adaptive rate C-ARQ scheme over block fading channels, when the number of retransmission attempts per packet at the relay node is finite. Then aiming at maximizing the spectral efficiency, we propose an AMC-based rate adaptation policy (per frame) for the relay channel, which guarantees a prescribed average packet loss rate constraint. As a side result, an adaptive rate T-ARQ scheme is proposed which is suitable for the scenarios where only single-link communication is allowed. The existing work on adaptive rate T-ARQ such as [15] does not count the outage event as a source of packet loss. In this situation, the packets are buffered for transmission in subsequent frames disregarding the imposed delay. However, we consider a more

realistic model to capture the effects of the delay experienced by a packet in the event of an outage as it contributes towards packet loss.

In addition, for the scenario where only the channel statistics (and not the per frame channel state information (CSI)) are available, an optimized rate selection policy is presented. As an interesting application of the proposed adaptive rate C-ARQ scheme, we also consider AMC design and blockage mitigation for LMSC in presence of a relay. Numerical results for both terrestrial links with Rayleigh fading and slowly varying LMSC links show that the proposed cross-layer design for adaptive rate C-ARQ scheme considerably improves the spectral efficiency performance. In particular, several schemes are considered in the settings under consideration for comparison: (i) a joint AMC and T-ARQ scheme designed for the direct S-D link and, (ii) an optimized fixed rate C-ARQ, when optimized transmission rates at the source and relay nodes are chosen based on channel statistics. Moreover, the results on LMSC system, where the channels experience frequent outage and are highly correlated, demonstrate that because of the relay channel diversity an even better performance is achieved.

The rest of this paper is organized as follows. Sec. II describes the system and channel model. In Sec. III, we derive exact closed-form expressions for the average SE and the PLR of an adaptive rate C-ARQ scheme. We then present a cross-layer approach aiming at maximizing the SE subject to packet-level QoS constraints in Sec. IV. We also describe the C-ARQ in a fixed rate scenario and the performance of a T-ARQ scheme. In Sec. V, we consider the application of the proposed scheme for LMSC. Numerical results are provided in Sec. VI, while the concluding remarks are presented in Sec. VII.

II. SYSTEM MODEL

A. System Description

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As illustrated in Fig. 1, we consider an adaptive rate wireless network composed of a S node, a R node and a D node, where each node is equipped with a single antenna. At the S node, input packets from higher layers of stack are stored in the transmit buffer, grouped into frames, and then transmitted over the wireless channel on a frame by frame basis. As in [15], we assume that the transmit buffer at the source node is always loaded with packets and adopt the same packet and frame structure. Specifically, each frame has a fixed time duration and contains multiple packets based on the employed AMC mode, and each packet includes N_b information bits and a perfect CRC code for error detection. We assume a time-division orthogonal transmission for the nodes and that none of the nodes transmit and receive simultaneously. Adopting a DF strategy for the R node, the proposed cooperative-retransmission system operates as follows: First, the S node broadcasts a data frame to both D and R nodes and they listen. The D node checks the CRC for each packet within the received frame separately and broadcasts either a positive or a negative acknowledgement (ACK or NACK). If the relay receives a NACK message from the destination and it has successfully decoded the corresponding packet, it then retransmits this packet to the destination as frequently as it is received correctly or a maximum number of retransmissions (N_r) is reached. In case the packet is not correctly decoded at the R node, the *source* node retransmits the packet until successful decoding at the D or R node, or when there is no longer an opportunity for further retransmissions. Otherwise, the node S transmits a new data frame and the said procedure is repeated.

In this paper, we focus on a specific scenario of interest in which, the receiver at the D node drops the corrupted packets and only attempts to decode based on the latest retransmitted packet (similar to [1], [6], [7]). Indeed, combining the packets at the destination may enhance the system performance. However, it in turn increases the receiver complexity at the destination. In

particular, the receiver needs to store the corrupted packets and mix them appropriately which may not be affordable when the destination is intended to be of limited complexity (e.g., a mobile terminal). We also consider cooperation with a single well placed relay node chosen based on a given relay selection mechanism. Further considerations on the system design such as relay selection strategies and packet-combining at the receiver are beyond the scope of this work and are left for future investigation.

B. Channel Models and AMC Modes

The S-D, R-D and S-R wireless links are modeled as flat-fading channels with AWGN and stationary power gains h_1 , h_2 and h_3 , respectively. We adopt a block fading model for the S-D, R-D and S-R channel gains, so that the channel gains remain constant over a frame duration but may vary from one frame to another [15]-[16]. In the subsequent analysis, we consider the same noise variance σ^2 for all channels and also the same constant transmit power level \bar{P} for S and R nodes. The instantaneous received SNR at the destination for the S-D and R-D channels are thus given by the random variables (r.v.) $\gamma_1 = \bar{P}h_1/\sigma^2$ and $\gamma_2 = \bar{P}h_2/\sigma^2$, with the probability density function (pdf), $p_{\gamma_1}(\gamma_1)$ and $p_{\gamma_2}(\gamma_2)$, respectively. Similarly, the received SNR at the R node is $\gamma_3 = \bar{P}h_3/\sigma^2$ with pdf $p_{\gamma_3}(\gamma_3)$.

At the physical layer, adaptive modulation and coding is employed for both S-D and R-D links based on their corresponding channel state information. To employ the AMC, the entire SNR range of S-D and R-D links are divided into N and M non-overlapping consecutive intervals, respectively. When the S-D channel SNR γ_1 falls in the interval $[\Gamma_{1,n}, \Gamma_{1,n+1})$, $n = 1, \dots, N$, $\Gamma_{1,1} = 0$, $\Gamma_{1,N+1} = \infty$, the mode n of AMC is chosen and the source transmits with rate $R_{1,n}$ (bits/symbol) from the rate set $\mathcal{R}_1 = \{R_{1,n}\}_{n=1}^N$. Note that the rate $R_{1,n}$ reflects the

modulation and coding rates utilized for mode n . A particular set of modes is illustrated in Table I. Assume that in the relay transmission, the R-D channel SNR is in the interval $[\Gamma_{2,m}, \Gamma_{2,m+1})$, $m = 1, 2, \dots, M$, $\Gamma_{2,1} = 0$, $\Gamma_{2,M+1} = \infty$, the relay transmits with rate $R_{2,m}$ (bits/symbol) from the rate set $\mathcal{R}_2 = \{R_{2,m}\}_{m=1}^M$. In the following, without loss of generality, an identical rate set is considered for both source and relay nodes, i.e., $\mathcal{R}_1 = \mathcal{R}_2 = \{R_n\}_{n=1}^N$. The set of SNR thresholds determining different transmission modes are denoted by $\Gamma_i \triangleq [\Gamma_{i,n}]_{n=2,\dots,N}$, $i = 1, 2$.

To enable the analysis and design in the sequel, the packet error rate (PER) over mode n is approximated by the following expression that is verified in [15]

$$PER_n(\gamma) \approx \begin{cases} 1, & \gamma < \Gamma_{pn} \\ a_n \exp(-g_n \gamma), & \gamma \geq \Gamma_{pn} \end{cases} \quad (1)$$

in which the parameters $\{a_n, g_n, \Gamma_{pn}\}$ are determined by curve fitting to the exact PER of mode n .

Before closing this section, it is worth noting that in the considered adaptive rate scheme, the CSI refers to the SNR intervals that the SNR of the S-D and R-D links fall into. In other words, to facilitate rate adaptation at the S and R nodes, only a few bits ($\lceil \log_2 N \rceil$) of feedback suffices for them to set the transmission modes. In this case, we assume that the CSI is estimated perfectly at the D node and is fed back reliably without delay to the S and R nodes. The system design considerations, when these assumptions are violated, are left for future investigation

III. ADAPTIVE RATE C-ARQ: PERFORMANCE ANALYSIS

We aim at developing a cross-layer link adaptation scheme for the relay channel when a C-ARQ protocol at the data link layer is employed and the following QoS requirements are imposed by the packet service.

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C1) Delay constraint: The maximum number of retransmission attempts per packet is limited to N_r . Accordingly, if a packet is not received correctly after N_r retransmission attempts, it is considered lost.

C2) PLR QoS constraint: At the data-link layer, the packet loss probability following N_r possible retransmissions is to be less than a target PLR, P_{loss} .

To this end, in this section we first analyze the performance of the joint C-ARQ and AMC scheme in terms of system spectral efficiency and packet loss rate; in the next section we then optimize the SE subject to a PLR constraint. In the subsequent analysis of this section, as is common in the literature (see, e.g., [15]), the channel gains are assumed to be independent and identically distributed during possible retransmissions of a packet.

A. Spectral Efficiency

We define the average spectral efficiency as the average number of *accepted* information bits per *transmitted* symbol (see, e.g., [17]). In the presented model, consider a packet, containing N_b information bits, which uses N_s channel symbols to be delivered to the destination. In general, this packet may be received at the D node after $l+1$ *source* (re)transmissions and k retransmissions by the *relay* node where $0 \leq k+l \leq N_r$. Here, $l=0$ denotes the original transmission and $k=0$ represents the case that all possible (re)transmissions of a packet are performed over the S-D link. The r.v.'s l and k depend on the channel noise over different packet transmissions. Also, since the channels undergo block fading, different rates R_{n_l} and R_{m_k} over S-D and R-D links in l -th and k -th attempts are used, respectively, and consequently different number of symbols carry the packet in different (re)transmissions. Accordingly, the number of accepted information bits per transmitted symbol is a r.v. which takes the value of $N_b/N_s =$

$1/\left(\sum_{i=0}^l 1/R_{n_i} + \sum_{j=1}^k 1/R_{m_j}\right)$, if a packet is successfully received at the D node, and zero otherwise. Finding the statistical description of the corresponding r.v.'s and averaging w.r.t the channel noise and SNR realizations, the average SE is then obtained.

Proposition 1: The average spectral efficiency (bits/symbol) of the adaptive rate cooperative N_r -truncated ARQ protocol, over a wireless block fading relay channel, is given by

$$\begin{aligned} & \eta^{\text{A-CARQ}}(\mathbf{\Gamma}_1, \mathbf{\Gamma}_2) \\ &= \sum_{l=0}^{N_r} \sum_{k=0}^{N_r-l} \sum_{n_0=1}^N \cdots \sum_{n_l=1}^N \sum_{m_1=1}^N \cdots \sum_{m_k=1}^N \frac{\prod_{i=0}^{l-1} \overline{PER}_{1,n_i} \overline{PER}_{3,n_i}}{\Omega(\mathbf{n}_l, \mathbf{m}_k)} \\ & \times \left\{ (1 - \overline{PER}_{1,n_l}) I_{\{k=0\}} + \overline{PER}_{1,n_l} (1 - \overline{PER}_{3,n_l}) (1 - \overline{PER}_{2,m_k}) \prod_{j=1}^{k-1} \overline{PER}_{2,m_j} I_{\{k \geq 1\}} \right\} \\ & \times \prod_{i=0}^l \pi_{1,n_i} \prod_{j=1}^k \pi_{2,m_j} \end{aligned} \quad (2)$$

where $\mathbf{n}_l \triangleq [n_i]_{i=1,\dots,l}$, $\mathbf{m}_k \triangleq [m_j]_{j=1,\dots,k}$, $\Omega(\mathbf{n}_l, \mathbf{m}_k) \triangleq \sum_{i=0}^l 1/R_{n_i} + \sum_{j=1}^k 1/R_{m_j}$, and $I_{\{x\}} = 1$ if x is true, and zero otherwise. Also, the product terms when the upper index is less than the lower index are regarded as unity. For a particular packet, the AMC mode n_i at the i -th source transmission and m_j at the j -th relay retransmission are chosen with probabilities $\pi_{1,n_i} \triangleq \int_{\Gamma_{1,n_i}}^{\Gamma_{1,n_i+1}} p_{\Gamma_1}(\gamma) d\gamma$ and $\pi_{2,m_j} \triangleq \int_{\Gamma_{2,m_j}}^{\Gamma_{2,m_j+1}} p_{\Gamma_2}(\gamma) d\gamma$, respectively. Also, the average PER by choosing mode m_j over the R-D link and mode n_i over the S-D and S-R links are given by

$$\overline{PER}_{2,m_j} \triangleq \frac{1}{\pi_{2,m_j}} \int_{\Gamma_{2,m_j}}^{\Gamma_{2,m_j+1}} PER_{m_j}(\gamma) p_{\Gamma_2}(\gamma) d\gamma, \quad (3)$$

$$\overline{PER}_{1,n_i} \triangleq \frac{1}{\pi_{1,n_i}} \int_{\Gamma_{1,n_i}}^{\Gamma_{1,n_i+1}} PER_{n_i}(\gamma) p_{\Gamma_1}(\gamma) d\gamma, \quad (4)$$

$$\overline{PER}_{3,n_i} \triangleq \int_0^\infty PER_{n_i}(\gamma) p_{\Gamma_3}(\gamma) d\gamma. \quad (5)$$

Proof: The proof is provided in Appendix A. ■

For the particular case where there is a single transmission over the S-D link, i.e., $N_r=0$, from (2), SE is $\sum_{n=1}^N R_n (1 - \overline{PER}_{1,n}) \pi_{1,n}$. It is also observed that, for a particular packet decoded correctly at the D node following $l + 1$ source and k relay transmissions, the selected rates over different channels appear through the term $1/\Omega(\mathbf{n}_l, \mathbf{m}_k)$ which is actually the scaled Harmonic mean. This implies that, if either S-D or R-D channel in one transmission attempt has a poor quality and consequently a low AMC rate is selected, the net rate takes a small value. Thus, a well-placed relay node, creating a high quality R-D channel for most of the time, can help in increasing the average spectral efficiency.

B. Packet Loss Rate Performance

The PLR at the data link layer refers to the probability that a packet is not received correctly at the destination after original transmission by the source and possible N_r retransmissions by the source and/or the relay. In the described model, consider a particular data packet, which is only decoded correctly at the R node after $l+1$, $0 \leq l \leq N_r$ source transmissions, whereas it is still erroneous at the D node. Suppose that even the N_r-l relay retransmissions do not help the D node correctly decode the corresponding packet. This constitutes a packet loss event and of course depends on the channel noise and SNR realizations over different packet (re)transmissions. Thus, by finding the statistical description of the corresponding processes and applying the statistical expectation to the probability of packet loss event the average PLR may be computed.

Proposition 2: The average PLR of the adaptive rate cooperative N_r -truncated ARQ protocol, over a wireless block fading relay channel, is given by

$$\begin{aligned} \overline{PLR}^{\text{A-CARQ}}(\mathbf{\Gamma}_1, \mathbf{\Gamma}_2) \\ = \sum_{l=0}^{N_r} (\overline{PER}_{(1,3)})^l \{ \overline{PER}_1 I_{\{l=N_r\}} + (\overline{PER}_1 - \overline{PER}_{(1,3)}) (\overline{PER}_2)^{N_r-l} I_{\{l < N_r\}} \} \end{aligned} \quad (6)$$

where $\overline{PER}_1 = \sum_{n=1}^N \overline{PER}_{1,n} \pi_{1,n}$ shows the average PER over the S-D link (Similarly \overline{PER}_2). Also, $\overline{PER}_{(1,3)} = \sum_{n=1}^N \overline{PER}_{1,n} \overline{PER}_{3,n} \pi_{1,n}$ denotes the average rate at which the sent packet by the source is erroneously received at both the relay and destination.

Proof: The proof is provided in Appendix B. ■

For a particular case where the S-R link has a very high quality i.e., $\overline{PER}_{(1,3)} \cong 0$, the average PLR is $\overline{PER}_1 (\overline{PER}_2)^{N_r}$ which exponentially decreases by increasing N_r .

C. Special Case: Performance Analysis of Traditional ARQ scheme

In the traditional ARQ scheme, which is studied in conjunction with AMC in, e.g., [15] and [17], only the S-D link is available for communications. The source retransmits the erroneously received packets upon receiving a NACK message from the destination. The T-ARQ scheme is therefore a special case of the considered C-ARQ scheme when the S-R link is always blocked, and thus the source node performs all the retransmissions. The following corollaries describe the performance of this scheme.

Corollary 1: The average spectral efficiency of the adaptive rate N_r -truncated ARQ protocol, over a wireless link with block fading, is given by

$$\eta^{\text{A-TARQ}}(\mathbf{\Gamma}_1) = \sum_{l=0}^{N_r} \sum_{n_0=1}^N \dots \sum_{n_l=1}^N \frac{1}{\Omega(\mathbf{n}_l)} (1 - \overline{PER}_{1,n_l}) \pi_{1,n_l} \prod_{k=0}^{l-1} \overline{PER}_{1,n_k} \pi_{1,n_k} \quad (7)$$

where $\mathbf{n}_l \triangleq [n_i]_{i=1, \dots, l}$, and $\Omega(\mathbf{n}_l) \triangleq \sum_{k=1}^l 1/R_{n_k}$.

Proof: This is obtained from Proposition 1 by considering $\overline{PER}_{3,n} = 1$, $n = 1, \dots, N$. ■

Corollary 2: The average PLR of the adaptive rate N_r -truncated ARQ protocol, over a wireless link with block fading, is as follows

$$\overline{PLR}^{A-TARQ}(\Gamma_1) = (\overline{PER}_1)^{N_r+1}. \quad (8)$$

Proof: This is obtained from Proposition 2 by considering $\overline{PER}_{3,n} = 1$ which results in $\overline{PER}_{(1,3)} = \overline{PER}_1$. ■

It is worth noting that the SE expressions in [15] and [17] for T-ARQ scheme are approximations of the defined SE in Sec. III. A. Moreover, the PLR expressions in [15] and [17] do not consider the delay experienced by the packets in the buffer (lost transmission opportunity) during outage events as a source of packet loss for higher layers.

IV. SPECTRAL EFFICIENCY OPTIMIZED C-ARQ: CROSS-LAYER DESIGN

In this section, we propose a cross-layer approach to design an optimized rate adaptation policy for the system in Fig. 1 such that the system SE is maximized, while a PLR constraint is provisioned. To this end, we first focus on the scenario described in Sec. II.B, where the S and R nodes adapt their transmission rates in each frame based on the received CSI feedback from the D node. We then devise a rate selection algorithm for the scenario, where providing per frame feedback is not feasible.

A. Adaptive rate cooperative ARQ scheme

In order to design an optimized rate adaptation policy for the scheme described in Sec. II.A we use the performance metrics derived in the Sec. III. The desired optimization problem is formulated as follows

$$\begin{aligned} \text{(P1)} \quad & \max_{\{\Gamma_{i,N} \geq \dots \geq \Gamma_{i,2} \geq \Gamma_{i,1} = 0, \quad i=1,2\}} \eta^{A-CARQ}(\Gamma_1, \Gamma_2) \quad \text{subject to} \\ & \overline{PLR}^{A-CARQ}(\Gamma_1, \Gamma_2) \leq P_{loss} \end{aligned} \quad (9)$$

where the PLR constraint (9) is described in Proposition 2. Finding an optimal solution to (P1) is formidable as the objective function and the constraint are related to AMC thresholds through complicated nonlinear equations.

To find an efficient solution with reasonable complexity, a suboptimum solution is devised in which the average PER for non-outage AMC modes ($n > 1$) of S-D and R-D links are assumed fixed at $P_{t,1}$ and $P_{t,2}$, respectively. This is performed by setting the AMC threshold $\Gamma_{i,n}$ for mode n over link i such that

$$\overline{PER}_{i,n} = P_{t,i}, \quad i = 1,2, \quad n = 2,3, \dots, N \quad (10)$$

Accordingly, the AMC thresholds of link i are obtained as a function of a single variable $P_{t,i}$. An efficient search algorithm to obtain Γ_i from (10) is described in Table II. It should be noted that, the idea of imposing a fixed average PER over each non-outage AMC mode is used in the literature to design constant power AMC for point to point schemes (see e.g., [18]). Considering (10) in (P1), the new optimization problem is formulated as

$$(P2) \quad \max_{0 \leq P_{t,1}, P_{t,2} \leq 1} \eta^{\text{A-CARQ}}(P_{t,1}, P_{t,2}) \quad \text{subject to} \\ \overline{PLR}^{\text{A-CARQ}}(P_{t,1}, P_{t,2}) \leq P_{\text{loss}}. \quad (11)$$

To find the optimal target PER pair $(P_{t,1}^*, P_{t,2}^*)$, the *penalty function method* is adopted first to convert (P2) to an unconstrained optimization problem [19, ch. 9]. Accordingly, the term $\alpha(P_{t,1}, P_{t,2}) \triangleq (\max\{\overline{PLR}^{\text{A-CARQ}}(P_{t,1}, P_{t,2}) - P_{\text{loss}}, 0\})^2$ with a *very large* penalty parameter μ is added to the objective of (P2) to form the augmented SE as

$$\theta(P_{t,1}, P_{t,2}, \mu) \triangleq \eta^{\text{A-CARQ}}(P_{t,1}, P_{t,2}) - \mu\alpha(P_{t,1}, P_{t,2}). \quad (12)$$

The augmented SE takes a very small (perhaps negative) value, when the constraint is violated

$(\overline{PLR}^{\text{A-CARQ}}(P_{t,1}, P_{t,2}) > P_{\text{loss}})$ and it equals SE if the constraint is satisfied. Consider the optimal solution of (P2) as $(P_{t,1}^*, P_{t,2}^*)$ and define $\mathcal{P} \triangleq \{(P_{t,1}, P_{t,2}): 0 \leq P_{t,1}, P_{t,2} \leq 1\}$. Then, since the average SE and PLR are continuous functions of target PERs (resp. the augmented SE), according to Theorem 9.2.2 in [19, p. 477] we have: (i) $\eta^{\text{A-CARQ}}(P_{t,1}^*, P_{t,2}^*) = \lim_{\mu \rightarrow \infty} \max_{(P_{t,1}, P_{t,2}) \in \mathcal{P}} \theta(P_{t,1}, P_{t,2}, \mu)$, and (ii) $\lim_{\mu \rightarrow \infty} \mu \alpha(P_{t,1}^*(\mu), P_{t,2}^*(\mu)) = 0$, where $(P_{t,1}^*(\mu), P_{t,2}^*(\mu))$ maximizes $\theta(P_{t,1}, P_{t,2}, \mu)$ for a given μ over the set \mathcal{P} . In practice, to find the optimal solution, one can set a stop criterion ε (e.g., $=10^{-10}$) and an initial parameter μ (e.g., $=10^2$), and then iteratively increase μ such that $\mu \alpha(P_{t,1}^*(\mu), P_{t,2}^*(\mu)) < \varepsilon$ [19, p. 484].”

Our extensive numerical experiments show that the augmented SE in (12) is a unimodal function [19] of target PERs (see Fig. 2). Therefore, a fast two dimensional numerical search algorithm, e.g., based on the Cyclic Coordinate method [19], can be devised to find the optimized target PERs as the solution of

$$(P_{t,1}^*, P_{t,2}^*) = \operatorname{argmax}_{(P_{t,1}, P_{t,2})} \theta(P_{t,1}, P_{t,2}, \mu). \quad (13)$$

To find the AMC thresholds (Γ_1^*, Γ_2^*) from (10) for the given target PER pair $(P_{t,1}^*, P_{t,2}^*)$ the threshold search algorithm in Table II is employed. To obtain a solution to the nonlinear equation in step 2 of this algorithm, a simple root finding approach, e.g., the bisection method, may be invoked. In Sec. VI, it is demonstrated that the proposed rate adaptation design algorithm improves the performance noticeably when compared to the cases that the target PERs are not assigned in an optimized manner.

B. Fixed rate cooperative ARQ scheme

In general, rate adaptation in a wireless relay network as depicted in Fig. 1, requires the channel CSI for both the S-D and R-D links. In some scenarios providing instantaneous (per frame) CSI may not be feasible. In such cases, an alternative cross-layer design may be invoked to obtain the optimized fixed transmission rates of the S-D and R-D links provided that the channel statistics of S-D, S-R and R-D are available at the D node. For example, for wireless Rayleigh block fading channel model, the channel statistics refers to the mean channel SNR which still may be updated over a longer than frame period.

Let us consider the problem of optimized rate pair (R_n^*, R_m^*) selection for the source and relay nodes, based on the following optimization problem,

$$(P3) \quad \max_{1 \leq n, m \leq N} \eta^{\text{F-CARQ}}(n, m) \quad \text{subject to}$$

$$\overline{PLR}^{\text{F-CARQ}}(n, m) \leq P_{\text{loss}}, \quad (14)$$

in which the corresponding metrics are expressed as in the next corollary.

Corollary 3: The average SE and PLR of the fixed rate cooperative N_r -truncated ARQ protocol, over a wireless block fading relay channel, is given by

$$\eta^{\text{F-CARQ}}(n, m) = \sum_{l=0}^{N_r} \sum_{k=0}^{N_r-l} \frac{1}{(l+1)/R_n + k/R_m} (\overline{PER}_1(n) \overline{PER}_3(n))^l$$

$$\times \{(1 - \overline{PER}_1(n)) I_{\{k=0\}} \quad (15)$$

$$+ \overline{PER}_1(n) (1 - \overline{PER}_3(n)) (1 - \overline{PER}_2(m)) (\overline{PER}_2(m))^{k-1} I_{\{k \geq 1\}}\}$$

$$\overline{PLR}^{\text{F-CARQ}}(n, m) = \sum_{l=0}^{N_r} \left(\overline{PER}_{(1,3)}(n) \right)^l \quad (16)$$

$$\times \{ \overline{PER}_1(n) I_{\{l=N_r\}} + (\overline{PER}_1(n) - \overline{PER}_{(1,3)}(n)) (\overline{PER}_2(m))^{N_r-l} I_{\{l < N_r\}} \}$$

where, using equation (1), the average PER of transmitting with mode n over link $i \in \{1,2,3\}$ is given by

$$\begin{aligned}
\overline{PER}_i(n) &\triangleq \int_0^\infty PER_n(\gamma) p_{\Gamma_i}(\gamma) d\gamma \\
&= \int_0^{\Gamma_{pn}} p_{\Gamma_i}(\gamma) d\gamma + \int_{\Gamma_{pn}}^\infty a_n \exp(-g_n \gamma) p_{\Gamma_i}(\gamma) d\gamma.
\end{aligned} \tag{17}$$

$$\text{and } \overline{PER}_{(1,3)}(n) \triangleq \int_0^\infty \int_0^\infty PER_n(\gamma_1) PER_n(\gamma_3) p_{\Gamma_1}(\gamma_1) p_{\Gamma_3}(\gamma_3) d\gamma_1 d\gamma_3.$$

Proof: Following the same procedure as in Appendices A and B and considering fixed transmission rates for S and R nodes it is straightforward to obtain (15) and (16).

In order to solve (P3), a simple numerical search method is devised as follows. We first select the rate pair (R_1, R_1) as an initial solution, and increase the transmission rates of source and relay successively to find the possible rate pairs which satisfy the PLR constraint in (14). The optimized rate pair (R_n^*, R_m^*) is then selected as a rate pair among the feasible rate pairs which maximizes the spectral efficiency in (15). One may devise more sophisticated search algorithms to obtain the solution. However in practice the set of rate pairs is limited and the proposed method can find the best solution with a low complexity.

V. APPLICATIONS TO BLOCKAGE MITIGATION IN LAND MOBILE SATELLITE LINKS

In this section, we consider the application of the proposed joint C-ARQ and AMC scheme in land mobile satellite communications. The aim is to facilitate efficient and reliable communications in presence of satellite channel variations and blockage.

Recently, utilizing the AMC in the LMSC systems is well motivated by the advances in channel estimation and predication techniques for tracking the time varying satellite channels [11]. Nevertheless, satellite to mobile links suffer from channel blockages, which appear as deep fades over long periods of time [20]. As an error-control mechanism, T-ARQ protocol is used to combat the burst errors of such channels [21][22]. However, this in turn increases the satellite load and the overall latency in the system, especially given the highly correlated nature of such

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channels and potentially large number of required retransmissions [7]. As validated in [7] and [23], cooperative relaying appears as a promising technique to mitigate the channel blockage and to extend the satellite coverage, at the expense of involving a relay terminal for packet retransmissions. To apply the proposed cross-layer design to LMSC, we first introduce the LMSC system and channel model. Then, for this specific application, we present system design considerations to efficiently mitigate the S-D channel outage with the aid of the relay terminal in a C-ARQ framework.

A. LMSC System and Channel Model

We consider the downlink of a packet based geosynchronous satellite system assisted with a relay terminal. In this system, the satellite acts as the source node, the relay node can be an airborne node, i.e., a high altitude platform station [24][25] or a satellite ground terminal, e.g., a gap filler [26], and the destination node is a mobile terminal. As in [7], we model each of the S-D and R-D channels by a two-state Markov blockage channel, where the states correspond to the unblocked and blocked modes. The satellite-relay channel is also assumed to be reliable [7]. This is a valid assumption in this setting as the suitable position of the relay node facilitates a strong S-R link with a direct line of sight.

In the unblocked channel state, the channel gain amplitude for the S-D and the R-D links, follow a Rician distribution due to the presence of a line of sight. As a result, the corresponding channel SNR γ follows a Chi-square distribution as below

$$p_{Rice}(\gamma) = \frac{(1+K)e^{-K}}{\bar{\gamma}^u} \exp\left(\frac{-(1+K)\gamma}{\bar{\gamma}^u}\right) I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}^u}}\right) \quad (18)$$

where $I_0(\cdot)$ is the modified Bessel function of order zero, and the parameters K and $\bar{\gamma}^u$ denote the Rice factor and the average SNR per symbol, respectively. In the blocked channel state, due

to the shadowing effect and lack of a line of sight, the mean received signal power follows a Lognormal distribution, and the amplitude of multipath fading obeys a Rayleigh distribution. As a consequence the channel SNR γ follows the following pdf [20]

$$p_{Ray/Log}(\gamma) = \int_0^\infty \frac{e^{-\gamma/w}}{w} \frac{\xi}{\sqrt{2\pi}\sigma^s w} \exp\left\{-\frac{(10\log_{10} w - \mu^s)^2}{2(\sigma^s)^2}\right\} dw \quad (19)$$

where $\xi = 10/\ln 10$. The parameters, μ^s and σ^s denote the mean and standard deviation of the channel SNR in the blocked state, respectively.

According to the above discussion, each realization of the channel SNR γ , is governed by the Lutz distribution as follows [20]

$$p_\Gamma(\gamma) = (1 - A)p_{Rice}(\gamma) + Ap_{Ray/Log}(\gamma) \quad (20)$$

where $0 \leq A \leq 1$ is the blocked state probability. Obviously, when the S-D channel experiences an outage, a direct communication may not be reliable. In such cases, since the relay terminal may be able to communicate with the source node reliably, we use a relay-assisted transmission protocol for LMSC system, which allows source data transmission via the relay link. The main idea here is that the relay node is positioned such that the outage probability for the corresponding R-D link is smaller compared to the direct S-D link (see Table III).

B. Performance Analysis of the Proposed Schemes for LMSC

In this section, the performance of the developed adaptive and fixed rate C-ARQ schemes in Sec. IV is analyzed for LMSC. To this end, the following assumptions are made: (i) The relay node in LMSC system is assumed to receive the source data reliably as in [7], and (ii) The relay node only retransmits the packet once, i.e., $N_r = 1$. The later assumption is due to the highly correlated nature of LMSC channels which makes more relay retransmissions inefficient. Moreover, the results in Sec. VI.C for uncorrelated channels demonstrate that one retransmission

suffices to achieve almost all of the SE gain. Accordingly the following corollaries present the SE and PLR performance of the joint AMC and C-ARQ scheme in LMSC.

Corollary 4: The average spectral efficiency of the adaptive rate cooperative ARQ protocol ($N_r = 1$), for a LMSC system is given by

$$\eta^{\text{A-CARQ}}(\mathbf{\Gamma}_1, \mathbf{\Gamma}_2) = \sum_{n=1}^N R_n (1 - \overline{\text{PER}}_{1,n}) \pi_{1,n} + \sum_{n=1}^N \sum_{m=1}^N \frac{R_n R_m}{R_n + R_m} \overline{\text{PER}}_{1,n} (1 - \overline{\text{PER}}_{2,m}) \pi_{2,m} \pi_{1,n} \quad (21)$$

where the probability $\pi_{i,n}$, $i = 1, 2$, $n = 1, 2, \dots, N$ is given by

$$\pi_{i,n} = \int_{\Gamma_{i,n}}^{\Gamma_{i,n+1}} p_{\Gamma_i}(\gamma) d\gamma \triangleq F(\Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i). \quad (22)$$

Here $\mathbf{c}_i \triangleq [A_i, K_i, \bar{\gamma}_i^u, \mu_i^s, \sigma_i^s]$ is a vector that contains the channel parameters of the i -th link, and the function $F(\cdot, \cdot, \cdot)$ is defined as

$$F(x, y, \mathbf{z}) \triangleq (1 - z_1) [Q_1(\sqrt{2z_2}, \sqrt{2xv}) - Q_1(\sqrt{2z_2}, \sqrt{2yv})] + z_1 [\phi_t(-x) - \phi_t(-y)] \quad (23)$$

where $\mathbf{z} \triangleq [z_1, \dots, z_5]$, $v \triangleq (1 + z_2)/z_3$, $Q_1(\cdot, \cdot)$ is the first order Marcum Q -function [27], and

the expression $\phi_t(s) \triangleq \int_0^\infty e^{-st} \frac{\xi}{\sqrt{2\pi z_5 t}} \exp\left\{-\frac{(10 \log_{10} t + z_4)^2}{2z_5^2}\right\} dt$, is the moment generating

function of the r.v. t which is Lognormally distributed with the mean $-z_4$ and variance $(z_5)^2$.

The average PER $\overline{\text{PER}}_{i,n}$, $i = 1, 2$, $n = 2, 3, \dots, N$ in (21) based on (3) is given as

$$\overline{\text{PER}}_{i,n} \triangleq \frac{H(\Gamma_{pn}, \Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i)}{F(\Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i)} \quad (24)$$

where

$$H(\Gamma_{pn}, \Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i) \triangleq \begin{cases} F(\Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i) + G(\Gamma_{pn}, \Gamma_{i,n+1}, \mathbf{c}_i), & \Gamma_{i,n} < \Gamma_{pn} \\ G(\Gamma_{i,n}, \Gamma_{i,n+1}, \mathbf{c}_i), & \Gamma_{i,n} \geq \Gamma_{pn} \end{cases}$$

and

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$G(x, y, \mathbf{z}) \triangleq$

$$(1 - z_1) \frac{a_n v}{g_n + v} \exp\left(\frac{-g_n z_2}{g_n + v}\right) \left[Q_1\left(\sqrt{\frac{2z_2 v}{g_n + v}}, \sqrt{2x(g_n + v)}\right) - Q_1\left(\sqrt{\frac{2z_2 v}{g_n + v}}, \sqrt{2y(g_n + v)}\right) \right] \\ + z_1 \int_0^\infty \frac{a_n}{g_n w + 1} \left[e^{-(g_n + 1/w)x} - e^{-(g_n + 1/w)y} \right] \frac{\xi}{\sqrt{2\pi} z_5 w} \exp\left\{-\frac{(10 \log_{10} w - z_4)^2}{2z_5^2}\right\} dw. \quad (25)$$

Proof: In this particular case, where the S-R link is reliable ($\overline{PER}_{3,n} = 0, n = 1, 2, \dots, N$) and one retransmission is allowed ($N_r=1$), the source never retransmits a packet ($l=0$) and the relay retransmits at most once ($k \in \{0, 1\}$). Using the fact that $\sum_{m_1=1}^N \pi_{2,m_1} = 1$, (2) is reduced to (22), where the expressions (22) and (24) are obtained by computing the integrals in (3) and (4) w.r.t the LMSC channel pdf in (20). ■

The next corollary presents a closed form expression for the average PLR.

Corollary 5: The average PLR of the adaptive rate cooperative ARQ protocol ($N_r = 1$), for a LMSC system is given by

$$\overline{PLR}^{\text{A-CARQ}}(\mathbf{\Gamma}_1, \mathbf{\Gamma}_2) = \left(\sum_{n=1}^N \overline{PER}_{1,n} \pi_{1,n} \right) \left(\sum_{m=1}^N \overline{PER}_{2,m} \pi_{2,m} \right). \quad (26)$$

Proof: Substituting $N_r = 1$ and $\overline{PER}_{3,n} = 0, n = 1, 2, \dots, N$ in Proposition 2 and using (22) - (25), deriving (26) is straightforward. ■

Note that for the proposed adaptive rate C-ARQ scheme in LMSC with $N_r = 1$, due to the relay channel diversity, channel gains in the transmission and possible retransmission of a packet are independent. Therefore, Propositions 1 and 2 are applied to obtain the performance metrics. Having obtained the average SE and the PLR of the adaptive rate C-ARQ scheme in LMSC, the optimization algorithm in Sec. IV is now used to find the optimized AMC policy at the S and R nodes.

As a final note, we consider the fixed rate C-ARQ as a promising scheme in the LMSC,

when the required CSI for rate adaptation may not be available due to the rapid channel gain
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variations. Following the same approach as that presented in Sec. III.B we can easily obtain the optimized fixed rate C-ARQ scheme for the LMSC system by using the following spectral efficiency and PLR measures

$$\eta^{\text{F-CARQ}}(n, m) = R_n[1 - \overline{\text{PER}}_1(n)] + \frac{R_n R_m}{R_m + R_n} \overline{\text{PER}}_1(n)[1 - \overline{\text{PER}}_2(n)] \quad (27)$$

$$\overline{\text{PLR}}^{\text{F-CARQ}}(n, m) = \overline{\text{PER}}_1(n) \overline{\text{PER}}_2(m) \quad (28)$$

where $\overline{\text{PER}}_i(n) \triangleq F(0, \Gamma_{pn}, \mathbf{c}_n) + G(\Gamma_{pn}, \infty, \mathbf{c}_n)$.

VI. PERFORMANCE EVALUATION

In this section, we first assess the complexity of the proposed adaptive and fixed rate C-ARQ schemes for practical implementation. Benchmark schemes for comparison are presented subsequently. We then investigate the performance of the proposed schemes over uncorrelated terrestrial links with Rayleigh fading model. Next, the packet communications performance over highly correlated LMSC channels with a Lutz's model is assessed.

It is assumed that S, R and D nodes lie on a straight line. To consider the path loss effects, the S-D distance is normalized to unity and the S-R and R-D distances are set to d and $1 - d$, respectively [13]. Let β denote the path loss exponent, which is set to 4 in the following experiments. Then, the average SNR of S-D, S-R and R-D channels are $\bar{\gamma}_1 = \bar{P}/\sigma^2$, $\bar{\gamma}_3 = \bar{P}d^{-\beta}/\sigma^2$ and $\bar{\gamma}_2 = \bar{P}(1 - d)^{-\beta}/\sigma^2$, respectively.

For both source and relay nodes, we use the seven AMC modes adopted by the IEEE802.11a standard. The AMC modes and their corresponding fitting parameters for a packet length $N_b = 1080$ bits are obtained in [31] and presented in Table I. Naturally, one may easily consider other AMC modes in the presented framework.

A. Complexity Considerations

The complexity of the proposed design algorithms for both adaptive rate and fixed rate C-ARQ schemes are assessed here. The optimized AMC thresholds (or the optimized rate pair) are determined at the destination during the design phase off-line and can be stored in a look up table. Next, during the operations, the source and relay select their transmission rates based on the quantized CSI (mode indices) fed back from the destination.

In the case of adaptive rate scheme, the design complexity of the algorithm mainly stems from (i) the threshold search algorithm in Table II for AMC design over S-D and R-D links, given a fixed target PER pair $(P_{t,1}, P_{t,2})$, and (ii) a two dimensional search algorithm to find the optimized target PER pair $(P_{t,1}^*, P_{t,2}^*)$ from (P2). In general, the computational complexity can be evaluated in terms of the number of iterations based on a root finding method to obtain the optimized solution [28]. Let $I_{i,n}, i = 1, 2, n = 2, 3, \dots, N$, denote the number of iterations needed to find the AMC threshold $\Gamma_{i,n}$, for a given $P_{t,i}$ based on a root finding method, e.g., the Bisection method [29], in the prescribed threshold level search algorithm. The value I_p also denotes the number of iterations needed to find $(P_{t,1}^*, P_{t,2}^*)$ based on (13) via a search method such as the Cyclic Coordinate method [19]. Then, the number of iterations needed to find the optimized thresholds $\Gamma_i^*, i = 1, 2$ is $I_p \sum_{i=1}^2 \sum_{n=2}^N I_{i,n}$. In practice, the feasible set of (13) and the practical range of channel SNRs are bounded. Thus, the number of iterations needed to find the optimized solutions is limited. In the fixed rate scenario, according to the method described in Sec. IV.B, the maximum number of iterations to find the optimized solution is N^2 , which is insignificant. Consequently, the design complexity of the proposed algorithms is acceptable.

Note that the optimized solutions are affected by the channel parameters including the statistics of S-D, R-D and S-R channels as well as the system parameters such as P_{loss} and AMC

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mode fitting parameters. During an admitted connection most of these parameters are fixed for a specific application and only the channel statistics may vary slowly. Therefore, the solutions can be obtained under several channel conditions off-line, and used for operations.

B. Schemes for Comparison

To evaluate the potential benefits of cross-layer design of C-ARQ and rate selection, the performance of C-ARQ based schemes is compared with their T-ARQ counterparts over both correlated and uncorrelated S-D channel. For uncorrelated channel case, the AMC thresholds for the rate-adaptive T-ARQ are determined by solving (P2) for the SE and PLR expressed in Corollaries 1 and 2. Also, for the fixed-rate T-ARQ scheme, the optimized source rate can be easily obtained as the solution of (P3) when the S-R channel is ideal and S-D and R-D channels are statistically identical.

For the case of correlated channels, a temporal correlation model as in [30] is adopted for the S-D channel. In [30], the effect of rate adaptation in conjunction with T-ARQ protocol is examined for slowly varying channels, where the channel gain remains constant over transmission and possible retransmissions of a packet. The proposed analytical design framework can be used in this setting following the next two steps: (i) The corresponding performance metrics including SE and PLR are derived using the analysis presented in Appendices A and B by considering equal channel gains for transmission and possible retransmissions of a packet, as follows

$$\eta^{\text{T-ARQ}}(\Gamma_1) = \sum_{n=1}^N R_n \pi_{1,n} - \sum_{l=1}^{N_r+1} \sum_{n=1}^N (R_n/h_l) \overline{PER}_{1,n}^{(l)} \pi_{1,n} \quad (29)$$

$$\overline{PLR}^{\text{T-ARQ}}(\Gamma_1) = \sum_{n=1}^N \overline{PER}_{1,n}^{(N_r+1)} \pi_{1,n} \quad (30)$$

where $h_l \triangleq l(l+1)$, $l = 1, 2, \dots, N_r$ and $h_l \triangleq N_r + 1$, $l = N_r + 1$. The value of $\overline{PER}_{1,n}^{(l)}$ is also obtained from (24), where a_n and g_n are substituted by $(a_n)^l$ and lg_n , respectively. (ii) Find the AMC thresholds using the threshold search algorithm introduced in Sec. IV with $\overline{PER}_{1,n} = P_t^*$. The value of the target PER P_t^* is set to maximize the spectral efficiency in (29), while satisfying the PLR constraint in (30). For the fixed-rate T-ARQ over correlated channel, the optimized source rate is picked as the solution of (P3), where the SE and PLR can be easily obtained by following the same approach as in the adaptive rate counterpart.

C. Experiments on Wireless Rayleigh Fading Channel

The performance of the proposed algorithm in Sec. IV.A to find the optimized target PERs of S-D and R-D links for the adaptive rate C-ARQ scheme is illustrated in Fig. 2. It is observed that an intelligent choice of the target PERs for the S-D and R-D links noticeably improves the spectral efficiency performance.

Fig. 3 compares the SE performance of the proposed adaptive and fixed rate C-ARQ schemes with $N_r = 1$. It is seen that the adaptive rate scheme considerably outperforms the optimized fixed rate scheme. This performance gain is attributed to using instantaneous per frame channel CSI at the source and relay nodes, compared to the case where only channel statistics are available. This observation signifies the role of exploiting channel CSI jointly with C-ARQ in the relay channel. From the QoS provisioning perspective, both schemes satisfy the PLR constraint above the same SNR threshold. This is because, in sever channel conditions the first AMC mode of adaptive rate scheme is dominant, which leads to the same reliability performance as the fixed rate scheme exploiting the lowest possible rate.

Fig. 4 depicts the average SE versus the average SNR of S-D link for different adaptive rate transmission schemes. It is observed that the point to point scheme ($N_r = 0$) even in the moderate SNR range cannot satisfy the PLR and delay-QoS requirements. The rationale behind this issue is that the most reliable arrangement of AMC thresholds, here always sending with BPSK modulation and half rate Convolutional code on a Rayleigh fading channel with $\bar{\gamma}_1 < 12\text{dB}$, cannot achieve $\overline{PLR} < 0.05$. This observation indicates the need for utilizing retransmission diversity for QoS constrained applications in wireless networks. Note that for the range of channel SNRs where (P2) is not feasible, i.e., the QoS constraint is not satisfied, the SE is assumed zero.

As evident in Fig. 4, the T-ARQ protocol with independent channels at different packet transmissions outperforms the point to point scheme. However, this scheme also suffers from the outages of the S-D channel. In fact, the C-ARQ protocol, benefiting from cooperative diversity, efficiently mitigates the effect of channel outage thereby leading to a dramatic QoS guarantee improvement over the joint AMC and T-ARQ scheme. Specifically for the case of $N_r = 1$, the joint C-ARQ and AMC scheme satisfies the constraint for $\bar{\gamma}_1 \geq 0\text{dB}$, while the T-ARQ scheme needs $\bar{\gamma}_1 \geq 5\text{dB}$ to satisfy the QoS constraint. An interesting observation here is that the joint AMC and C-ARQ scheme with delay constraint $N_r = 1$ outperforms the T-ARQ counterpart using $N_r = 3$ retransmissions. Moreover, C-ARQ with $N_r = 1$ captures almost all of the achievable spectral efficiency gain in the practical range of channel SNR.

Fig. 5 presents the effect of relay position on the performance of joint AMC and C-ARQ scheme with $N_r = 1$. It is immediately observed that choosing a well-placed relay node has a significant effect on the SE performance for the low and moderate SNR range, where the QoS constraints are hard to achieve.

In Fig. 6, we compare the average spectral efficiency of the optimized fixed rate schemes, selecting the transmission rate based on the channel statistics (average channel SNRs) for point to point (T-ARQ, $N_r = 0$), T-ARQ and C-ARQ schemes. It is observed that the C-ARQ scheme noticeably improves the spectral efficiency with respect to the T-ARQ scheme. This is mainly because the relay node (compared to the source node) is closer to the destination and facilitates a strong channel for retransmissions of a packet. This effectively alleviates the possible S-D channel outage and provides the required reliability to transmit high data rates. Moreover, utilizing possibly different transmission rates for the S and R nodes enables the system to change the rate for every slight variation of the channel statistics. This in turn leads to a smoother performance curve for the C-ARQ, when compared to the T-ARQ scheme.

The above results for uncorrelated Rayleigh fading channels suggest the proposed joint AMC and C-ARQ with $N_r = 1$ as a scheme with acceptable delay and high spectral efficiency for practical range of channel SNRs.

D. Experiments on LMSC System

Here, we investigate the performance of the proposed adaptive and fixed rate C-ARQ schemes introduced in Sec. IV over LMSC suffering from highly correlated channels. The channel parameters for the S-D and R-D channels, adopted from [20], are presented in Table III.

Fig. 7 shows the average SE of adaptive rate C-ARQ and T-ARQ schemes for different channel correlation conditions in LMSC. Because of the high probability of outage, the point to point scheme cannot satisfy the PLR QoS constraint even for high SNRs of the S-D channel, e.g., 17dB. As discussed in Sec. VI.B, the performance of T-ARQ scheme under two extreme cases of highly correlated and uncorrelated channel condition is also shown. The performance obtained

by exact modeling of temporal correlation is expected to lie in between the mentioned cases. It is M. Mardani, J. S. Harsini, F. Lahouti, and B. Eliasi, "Link adaptive and QoS provisioning Cooperative ARQ - Applications to Relay Assisted Land Mobile Satellite Communications," *To Appear in IEEE Transactions on Vehicular Technology*, 2011.

seen that the T-ARQ scheme has a poor performance in LMSC especially as the channels becomes more correlated. This is because, the blockage effects are repeated across transmissions of a packet thereby making further retransmissions inefficient. In contrast, the C-ARQ scheme, benefiting from independent channel gains in transmission and retransmission of a packet, provides the high reliability needed for data transmission in LMSC. This in turn leads to considerable performance improvement in SE with respect to T-ARQ schemes. Specifically, from the QoS provisioning perspective, the C-ARQ with $N_r = 1$ satisfies the PLR constraint for $\bar{\gamma}_1 > 5\text{dB}$, while the T-ARQ scheme is able to accomplish this only for $\bar{\gamma}_1 > 17\text{dB}$. These substantial QoS improvement and SE gains signify the role of relay retransmission for blockage mitigation in LMSC systems.

In Fig. 8, the spectral efficiency of the fixed rate C-ARQ and T-ARQ schemes for LMSC systems are plotted. As evident, thanks to the diversity provided by the relay node, the C-ARQ scheme satisfies the QoS constraint in the low SNR range of the S-D link. This enables the S and R nodes to select higher transmission rates and thereby results in much higher spectral efficiency when compared to the T-ARQ scheme.

Comparing the results in Sec. VI.C and Sec. VI.D, it is observed that the novel scheme presented yields a higher performance gain in LMSC systems. This is because, in this scenario the channel blockage effect is compensated effectively using a C-ARQ protocol as opposed to a T-ARQ.

VII. CONCLUSIONS

In this paper, we developed a cross-layer approach to design an adaptation scheme over the relay channel in the presence of C-ARQ at the data link layer to enhance the system performance for data packet transmission over block fading relay channels. The proposed scheme maximizes

the system spectral efficiency subject to a prescribed PLR constraint for delay constrained packet services. We have shown that the presented scheme and solutions can be well fitted to applications such as LMSC and help resolve the severe channel blockage effects. Numerical results indicate a considerable QoS provisioning and spectral efficiency gain when compared to systems such as AMC only at the physical layer, optimized fixed rate C-ARQ and joint T-ARQ and AMC scheme. This in turn validates the efficiency of the proposed cross-layer approach for QoS provisioning in wireless relay packet networks.

As the future extension of this work, the generalization of the proposed cross-layer analysis to consider the effects of 1) a relay selection algorithm, and 2) packet-combining at the destination node, is worth pursuing.

APPENDIX A

For the considered adaptive rate cooperative N_r -truncated ARQ protocol, the S and R node may retransmit the erroneously received packet at the destination, until it is received correctly or a maximum allowable number of retransmissions is reached. Therefore, each packet data, in general, encounters a vector of channel SNR realizations denoted by $\boldsymbol{\gamma} \triangleq (\gamma_1^{(0)}, \dots, \gamma_1^{(L)}, \gamma_3^{(0)}, \dots, \gamma_3^{(L)}, \gamma_2^{(1)}, \dots, \gamma_2^{(K)})$. Here, the r.v. $\gamma_1^{(i)}$ and $\gamma_3^{(i)}$, $i = 0, 1, \dots, L$ denote the SNR of S-D and S-R channels respectively for $L + 1$ *source* transmission attempts. Similarly, $\gamma_2^{(j)}$, $j = 1, 2, \dots, K$ is the SNR of R-D channel for K *relay* retransmissions. The r.v.'s $L, K \in \{0, 1, 2, \dots, N_r\}$ are constrained through $0 \leq L + K \leq N_r$ and depend on the channel noise. Here, $K=0$ means no retransmission is performed over the R-D link. Let R_{n_i} and R_{m_j} ; $n_i, m_j \in \{1, \dots, N\}$ show the selected rates by the S and R nodes when the channel SNRs $\gamma_1^{(i)}$ and $\gamma_2^{(j)}$ lie in the SNR intervals $[F_{1,n_i}, F_{1,n_i+1})$ and $[F_{2,m_j}, F_{2,m_j+1})$, respectively. Then, the number of

transmitted symbols per packet for the channel SNR $\gamma_1^{(i)}$ is N_b/R_{n_i} , and for the channel SNR $\gamma_2^{(j)}$ is N_b/R_{m_j} . Therefore, the total number of transmitted symbols for each accepted packet is $N_s = N_b\Omega(\mathbf{n}_K, \mathbf{m}_L)$, where $\Omega(\mathbf{n}_K, \mathbf{m}_L) \triangleq \sum_{i=0}^L 1/R_{n_i} + \sum_{j=1}^K 1/R_{m_j}$, $\mathbf{n}_L = [n_i]_{i=1,\dots,L}$, $\mathbf{m}_K = [m_j]_{j=1,\dots,K}$ and the pair (L, K) is statistically described as follows

$$(L, K) = \begin{cases} (0, 0), & T_1^{(0)}:s \\ (l, 0), & (T_1^{(0)}:f \cap T_3^{(0)}:f) \cap \dots \cap (T_1^{(l-1)}:f \cap T_3^{(l-1)}:f) \cap T_1^{(l)}:s, \quad l \geq 1 \\ (0, k), & (T_1^{(0)}:f \cap T_3^{(0)}:s) \cap (T_2^{(1)}:f \cap \dots \cap T_2^{(k-1)}:f \cap T_2^{(k)}:s), \quad k \geq 1 \\ (l, k), & (T_1^{(0)}:f \cap T_3^{(0)}:f) \cap \dots \cap (T_1^{(l-1)}:f \cap T_3^{(l-1)}:f) \cap (T_1^{(l)}:f \cap T_3^{(l)}:s) \\ & \cap (T_2^{(1)}:f \cap \dots \cap T_2^{(k-1)}:f \cap T_2^{(k)}:s), \quad k \geq 1, l \geq 1 \end{cases} \quad (31)$$

where $T_1^{(i)}$, $T_3^{(i)}$ and $T_2^{(j)}$ are the events indicating the success (s) or failure (f) of the i -th packet transmission over the S-D, S-R and the j -th packet transmission over R-D channel, respectively.

These events take the following probabilities

$$\begin{aligned} \Pr(T_1^{(i)}:f) &= PER_{n_i}(\gamma_1^{(i)}), \\ \Pr(T_3^{(i)}:f) &= PER_{n_i}(\gamma_3^{(i)}), \\ \Pr(T_2^{(j)}:f) &= PER_{m_j}(\gamma_2^{(j)}) \end{aligned}$$

Accordingly, the instantaneous SE is $\eta(\boldsymbol{\gamma}, L, K) = N_b/N_s = 1/\Omega(\mathbf{n}_L, \mathbf{m}_K)$ when the packet is accepted at the D node, and $\eta(\boldsymbol{\gamma}, L, K) = 0$ otherwise. The average spectral efficiency of the proposed joint cooperative truncated ARQ-AMC scheme is thus formulated as

$$\eta = \mathbb{E}_{\boldsymbol{\gamma}} \mathbb{E}_{(L,K)} [\eta(\boldsymbol{\gamma}, L, K) | \boldsymbol{\gamma}]. \quad (32)$$

Averaging with respect to the r.v. pair (L, K) , the inner expectation in (32) is given by

$$\eta(\boldsymbol{\gamma}) = \mathbb{E}_{(L,K)} [\eta(\boldsymbol{\gamma}, L, K) | \boldsymbol{\gamma}] = \sum_{l=0}^{N_r} \sum_{k=0}^{N_r-l} \frac{1}{\Omega(\mathbf{n}_l, \mathbf{m}_k)} \Pr(L=l, K=k | \boldsymbol{\gamma}). \quad (33)$$

Since the channel noise for successive transmissions of a packet are independent, using (31) and (33) and after some rearrangements, the joint probability mass function $\Pr(L = l, K = k)$ is determined as

$$\Pr(L = l, K = k | \boldsymbol{\gamma}) = \prod_{i=0}^{l-1} PER_{n_i}(\gamma_1^{(i)}) PER_{n_i}(\gamma_3^{(i)}) \left\{ \left(1 - PER_{n_l}(\gamma_1^{(l)})\right) I_{\{k=0\}} + PER_{n_l}(\gamma_1^{(l)}) \left(1 - PER_{n_l}(\gamma_3^{(l)})\right) \left(1 - PER_{m_k}(\gamma_2^{(k)})\right) \prod_{j=1}^{k-1} PER_{m_j}(\gamma_2^{(j)}) I_{\{k \geq 1\}} \right\} \quad (34)$$

where $I_{\{x\}}$ equals one when x is true, and zero otherwise. Also, the product terms when the upper index is less than the lower index is regarded as unity (e.g., if $l=0$, $\prod_{i=0}^{l-1} PER_{n_i}(\gamma_1^{(i)}) PER_{n_i}(\gamma_3^{(i)}) = 1$). In general one may apply the expectation operator to the instantaneous spectral efficiency in (34) to obtain the average spectral efficiency. However, such analysis would be complicated as it needs a statistical analysis of correlated channel gains on the possible retransmissions of a packet by the source and relay nodes. To simplify the analysis, it is assumed that the channel gains for retransmissions of a packet are independent. Thus, the average spectral efficiency in (32) is given by

$$\begin{aligned} \eta = \mathbb{E}_{\boldsymbol{\gamma}}[\eta(\boldsymbol{\gamma})] &= \sum_{l=0}^{N_r} \sum_{k=0}^{N_r-l} \sum_{n_0=1}^N \cdots \sum_{n_l=1}^N \sum_{m_1=1}^N \cdots \sum_{m_k=1}^N \frac{1}{\Omega(\mathbf{n}_l, \mathbf{m}_k)} \\ &\times \int_{\gamma_1^{(0)}=\Gamma_{1,n_0}}^{\Gamma_{1,n_0+1}} \cdots \int_{\gamma_1^{(l)}=\Gamma_{1,n_l}}^{\Gamma_{1,n_l+1}} \int_{\gamma_2^{(1)}=\Gamma_{2,m_1}}^{\Gamma_{2,m_1+1}} \cdots \int_{\gamma_2^{(k)}=\Gamma_{2,m_k}}^{\Gamma_{2,m_k+1}} \int_{\gamma_3^{(0)}=0}^{\infty} \cdots \int_{\gamma_3^{(l)}=0}^{\infty} \Pr(L = l, K = k | \boldsymbol{\gamma}) \\ &\times \prod_{i=0}^l p_{\Gamma_1}(\gamma_1^{(i)}) p_{\Gamma_3}(\gamma_3^{(i)}) d\gamma_1^{(i)} d\gamma_3^{(i)} \prod_{j=1}^k p_{\Gamma_2}(\gamma_2^{(j)}) d\gamma_2^{(j)} \end{aligned} \quad (35)$$

Using the definitions in (3) - (5) and after following a few steps, we obtain

$$\eta = \sum_{l=0}^{N_r} \sum_{k=0}^{N_r-l} \sum_{n_0=1}^N \cdots \sum_{n_l=1}^N \sum_{m_1=1}^N \cdots \sum_{m_k=1}^N \frac{1}{\Omega(\mathbf{n}_l, \mathbf{m}_k)} \prod_{i=0}^{l-1} \overline{PER}_{1,n_i} \overline{PER}_{3,n_i} \quad (36)$$

$$\times \left\{ (1 - \overline{PER}_{1,n_l}) I_{\{k=0\}} + \overline{PER}_{1,n_l} (1 - \overline{PER}_{3,n_l}) (1 - \overline{PER}_{2,m_k}) \prod_{j=1}^{k-1} \overline{PER}_{2,m_j} I_{\{k \geq 1\}} \right\}$$

$$\times \prod_{i=0}^l \pi_{1,n_i} \prod_{j=1}^k \pi_{2,m_j}$$

APPENDIX B

In the considered C-ARQ model each packet has $N_r + 1$ possible transmission opportunities by the S and R nodes to be decoded successfully at the D node. Imagine the scenario where after $H + 1$ transmissions by the source over S-D (and S-R) links, a packet arrives correctly at the R node while it is still in error at the D node. A packet loss event occurs when the D node still fails to decode the packet following the $G = N_r - H$ retransmissions by the R node. Thus, the lost packet encounters a vector of channel SNR realizations $\boldsymbol{\gamma} \triangleq (\gamma_1^{(0)}, \dots, \gamma_1^{(H)}, \gamma_3^{(0)}, \dots, \gamma_3^{(H)}, \gamma_2^{(1)}, \dots, \gamma_2^{(G)})$, where the r.v. $H \in \{0, 1, 2, \dots, N_r\}$ depends on the noise realizations over the channels. The statistical description of this r.v. is given by

$$H = \begin{cases} 0, & (T_1^{(0)}:f \cap T_3^{(0)}:s) \cap (T_2^{(1)}:f \cap \dots \cap T_2^{(N_r)}:f) \\ l, & (T_1^{(0)}:f \cap T_3^{(0)}:f) \cap \dots \cap (T_1^{(l-1)}:f \cap T_3^{(l-1)}:f) \cap (T_1^{(l)}:f \cap T_3^{(l)}:s) \\ & \cap (T_2^{(1)}:f \cap \dots \cap T_2^{(N_r-1)}:f), \quad 1 \leq l \leq N_r - 1 \\ N_r, & (T_1^{(0)}:f \cap T_3^{(0)}:f) \cap \dots \cap (T_1^{(N_r-1)}:f \cap T_3^{(N_r-1)}:f) \cap T_1^{(N_r)}:f \end{cases} \quad (37)$$

where the events $T_1^{(i)}$, $T_3^{(i)}$ and $T_2^{(j)}$ are defined in Appendix A. For the considered packet, let us denote the loss probability by $PLR(\boldsymbol{\gamma}, H)$. Defining the average PLR, $\overline{PLR} = \mathbb{E}_{\boldsymbol{\gamma}} \mathbb{E}_H [PLR(\boldsymbol{\gamma}, H) | \boldsymbol{\gamma}]$, and averaging w.r.t the noise effects, the instantaneous PLR is then derived as

$$\overline{PLR}(\boldsymbol{\gamma}) = \mathbb{E}_H [PLR(\boldsymbol{\gamma}, H) | \boldsymbol{\gamma}] = \sum_{l=0}^{N_r} \Pr(H = l | \boldsymbol{\gamma}). \quad (38)$$

where based on (37) the probability $\Pr(H = l|\boldsymbol{\gamma})$ is given by

$$\Pr(H = l|\boldsymbol{\gamma}) = \prod_{i=0}^{l-1} \text{PER}_{n_i}(\gamma_1^{(i)}) \text{PER}_{n_i}(\gamma_3^{(i)}) \times \left\{ \text{PER}_{n_l}(\gamma_1^{(N_r)}) \mathbb{I}_{\{l=N_r\}} + \text{PER}_{n_l}(\gamma_1^{(l)}) \left(1 - \text{PER}_{n_l}(\gamma_3^{(l)})\right) \prod_{j=1}^{N_r-l} \text{PER}_{m_j}(\gamma_2^{(j)}) \mathbb{I}_{\{l < N_r\}} \right\} \quad (39)$$

Apparently, for the case of $l = 0$ when all the retransmissions are accomplished by the relay node,

$$\Pr(H = 0|\boldsymbol{\gamma}) =$$

$$\text{PER}_{n_0}(\gamma_1^{(0)}) \mathbb{I}_{\{N_r=0\}} + \text{PER}_{n_0}(\gamma_1^{(0)}) \left(1 - \text{PER}_{n_0}(\gamma_3^{(0)})\right) \prod_{j=1}^{N_r} \text{PER}_{m_j}(\gamma_2^{(j)}) \mathbb{I}_{\{N_r>0\}}$$

Assuming the channel gains over different transmissions of a packet are independent, the average

PLR $\mathbb{E}_{\boldsymbol{\gamma}}[\text{PLR}(\boldsymbol{\gamma})]$ is obtained as

$$\begin{aligned} \overline{\text{PLR}} = & \sum_{l=0}^{N_r} \sum_{n_0=1}^N \cdots \sum_{n_l=1}^N \sum_{m_1=1}^N \cdots \sum_{m_{N_r-l}=1}^N \int_{\gamma_1^{(0)}=\Gamma_{1,n_0}}^{\Gamma_{1,n_0+1}} \cdots \\ & \int_{\gamma_1^{(l)}=\Gamma_{1,n_l}}^{\Gamma_{1,n_l+1}} \int_{\gamma_2^{(1)}=\Gamma_{2,m_1}}^{\Gamma_{2,m_1+1}} \cdots \int_{\gamma_2^{(N_r-l)}=\Gamma_{2,m_{N_r-l}}}^{\Gamma_{2,m_{N_r-l}+1}} \int_{\gamma_3^{(0)}=0}^{\infty} \cdots \int_{\gamma_3^{(l)}=0}^{\infty} \Pr(H = l|\boldsymbol{\gamma}) \quad (40) \\ & \times \prod_{i=0}^l p_{\Gamma_1}(\gamma_1^{(i)}) p_{\Gamma_3}(\gamma_3^{(i)}) d\gamma_1^{(i)} d\gamma_3^{(i)} \prod_{j=1}^{N_r-l} p_{\Gamma_2}(\gamma_2^{(j)}) d\gamma_j. \end{aligned}$$

Since $\Pr(H = l|\boldsymbol{\gamma})$ in (39) is separable over different channel SNR realizations, after some algebra and by using the definitions in (3) - (5) we have

$$\begin{aligned} \overline{\text{PLR}} = & \sum_{l=0}^{N_r} \prod_{i=0}^{l-1} \left(\sum_{n_i=1}^N \overline{\text{PER}}_{1,n_i} \overline{\text{PER}}_{3,n_i} \pi_{1,n_i} \right) \left\{ \left(\sum_{n_{N_r}=1}^N \overline{\text{PER}}_{1,n_{N_r}} \pi_{1,n_{N_r}} \right) \mathbb{I}_{\{l=N_r\}} \right. \\ & \left. + \left(\sum_{n_l=1}^N \overline{\text{PER}}_{1,n_l} (1 - \overline{\text{PER}}_{3,n_l}) \pi_{1,n_l} \right) \left(\prod_{j=1}^{N_r-l} \sum_{m_j=1}^N \overline{\text{PER}}_{2,m_j} \pi_{2,m_j} \right) \mathbb{I}_{\{l < N_r\}} \right\} \quad (41) \end{aligned}$$

Following some rearrangements, we arrive at the more convenient form

$$\overline{PLR} = \sum_{l=0}^{N_r} (\overline{PER}_{(1,3)})^l \{ \overline{PER}_1 \mathbf{1}_{\{l=N_r\}} + (\overline{PER}_1 - \overline{PER}_{(1,3)}) (\overline{PER}_2)^{N_r-l} \mathbf{1}_{\{l < N_r\}} \} \quad (42)$$

where $\overline{PER}_1 = \sum_{n=1}^N \overline{PER}_{1,n} \pi_{1,n}$ (similarly \overline{PER}_2) and $\overline{PER}_{(1,3)} = \sum_{n=1}^N \overline{PER}_{1,n} \overline{PER}_{3,n} \pi_{1,n}$.

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TABLE I
Transmission modes for AMC scheme and their corresponding fitting parameters [31].

Mode (n)	1	2	3	4	5	6	7
Modulation	BPSK	BPSK	QPSK	QPSK	16QAM	16QAM	64QAM
Coding rate	1/2	3/4	1/2	3/4	1/2	3/4	2/3
R_n (bits/symbol)	0.50	0.75	1	1.5	2	3	4
a_n	1448.089	311.0644	706.9783	264.0134	264.5420	171.0575	228.3775
g_n	11.8500	4.9410	2.8090	1.2220	0.6165	0.2500	0.09596
Γ_{pn} (dB)	-2.1171	0.6510	3.6842	6.5925	9.5655	13.1319	17.5279

TABLE II
Threshold search algorithm

Input: $P_{t,i}, i = 1,2$
Step1) Set $n = N$, and $\Gamma_{i,N+1} = \infty$.
Step2) $\Gamma_{i,n}$ is obtained as the unique solution of the nonlinear equation $\int_x^{\Gamma_{i,n+1}} (PER_n(\gamma) - P_{t,i}) p_{\Gamma_i}(\gamma) d\gamma = 0$ for $x, x \in (0, \Gamma_{i,n+1})$.
Step3) If $n = 2$, stop the algorithm, else $n \leftarrow n - 1$, and go to Step 1).
Output: $\Gamma_i(P_{t,i}), i = 1,2$

TABLE III
The S-D and R-D channel parameters in LMSC system when the power of unfaded satellite link is normalized to unity [20].

Channel	A	K (dB)	μ^s (dB)	σ^s (dB)
S-D	0.89	3.9	-11.5	2.0
R-D	0.24	10.2	-8.9	5.1

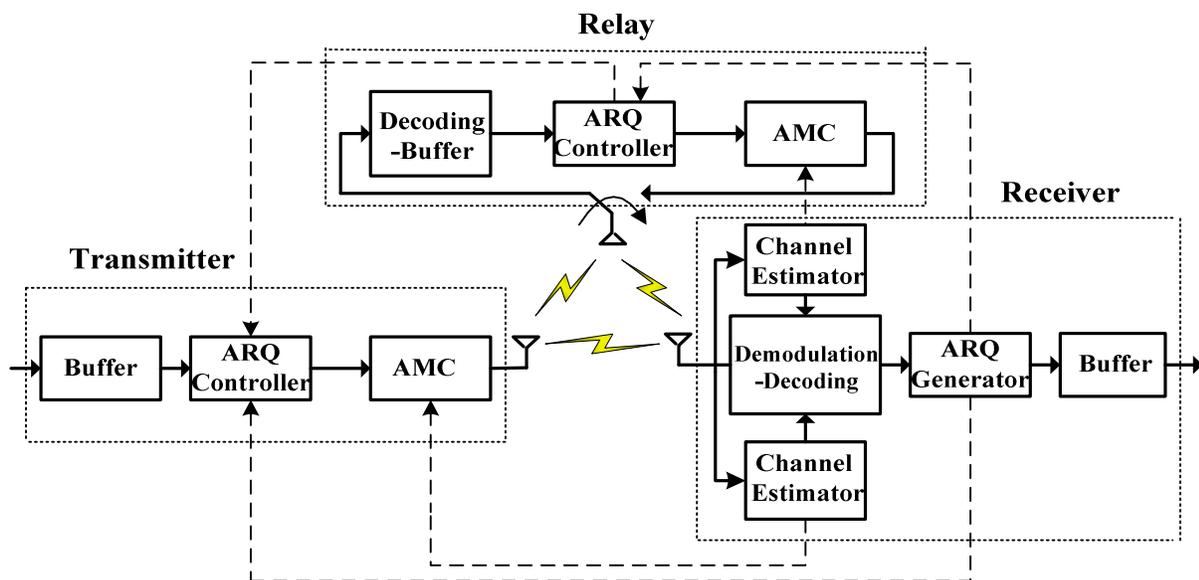


Fig. 1 System model.

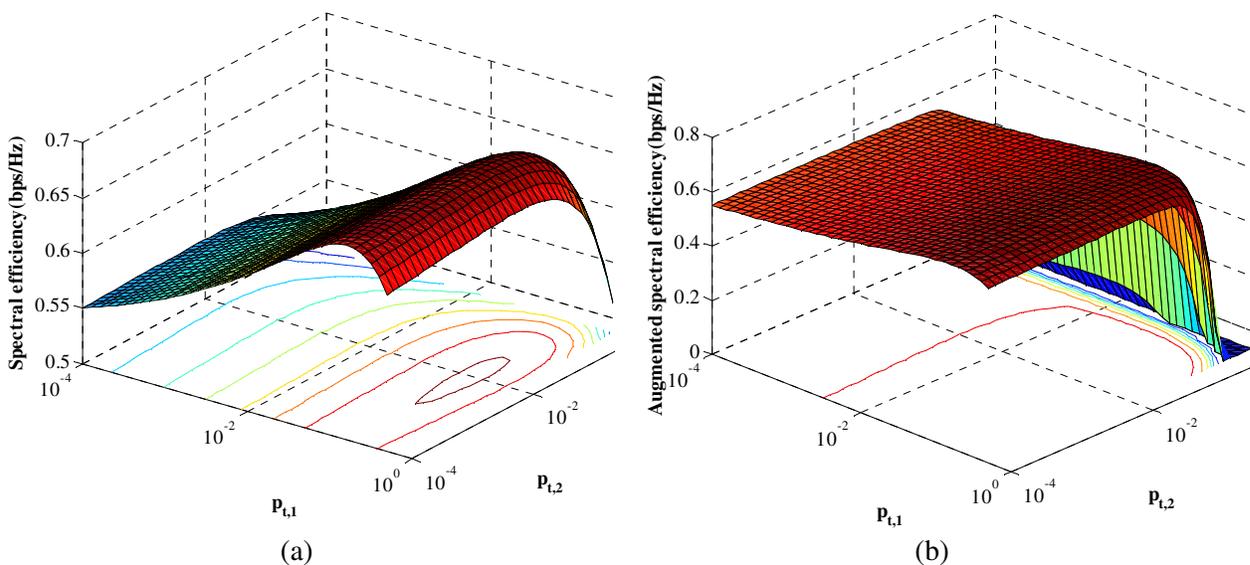


Fig. 2. (a) Spectral efficiency and (b) augmented spectral efficiency vs. the target PERs of S-D and R-D channels, $d = 0.5$, $P_{loss} = 0.05$, $\mu = 100$, $\bar{\gamma}_1 = 3\text{dB}$.

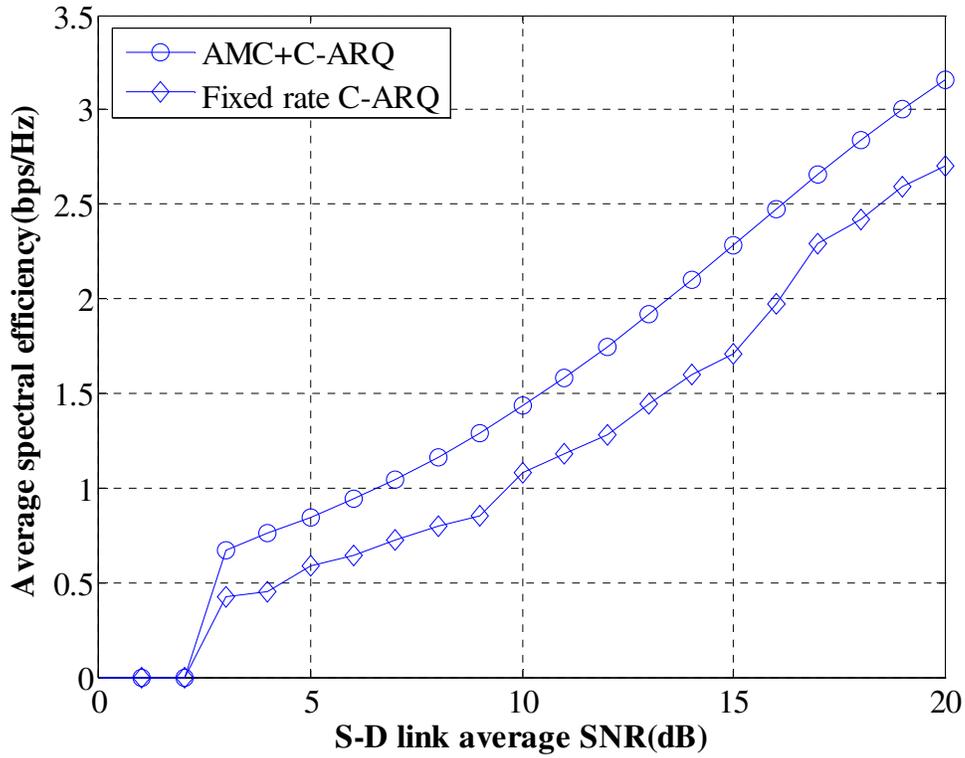


Fig. 3. Spectral efficiency comparison of adaptive rate and fixed rate C-ARQ schemes, $N_r=1$, $d = 0.5$, $P_{loss}=0.01$.

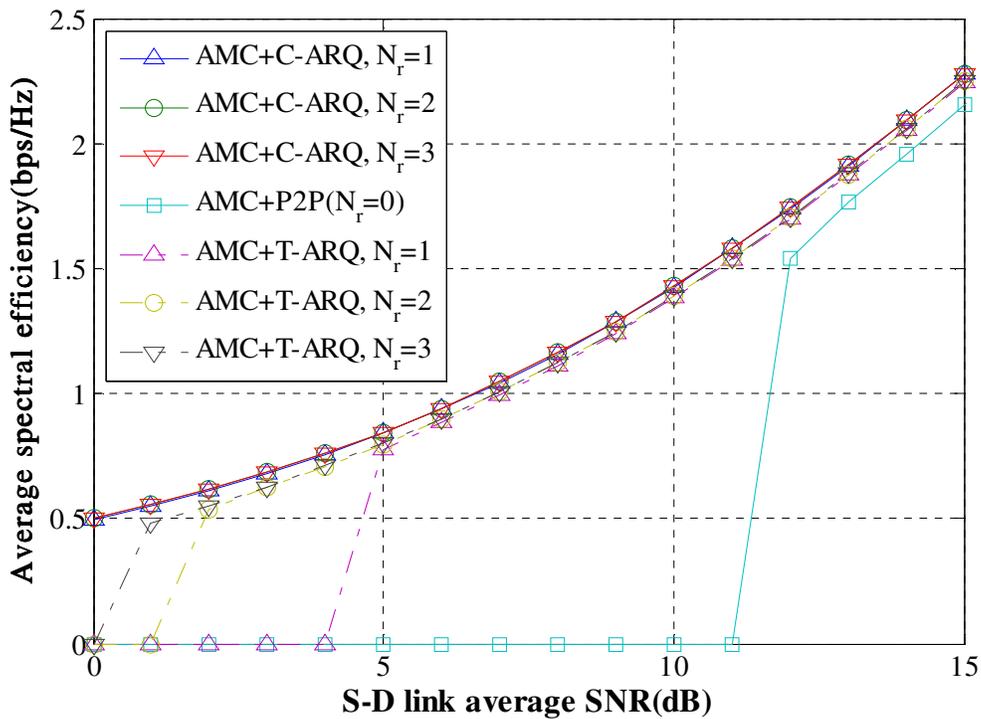


Fig. 4. Spectral efficiency vs. the average SNR of S-D channel for joint C-ARQ and AMC and AMC
M. Mardani, J. S. Harsini, F. Lahouti, and B. Eliasi, "Link adaptive and QoS provisioning Cooperative ARQ - Applications to Relay Assisted Land Mobile Satellite Communications," *To Appear in IEEE Transactions on Vehicular Technology*, 2011.

with/without T-ARQ schemes, $d = 0.5$, $P_{loss} = 0.05$.

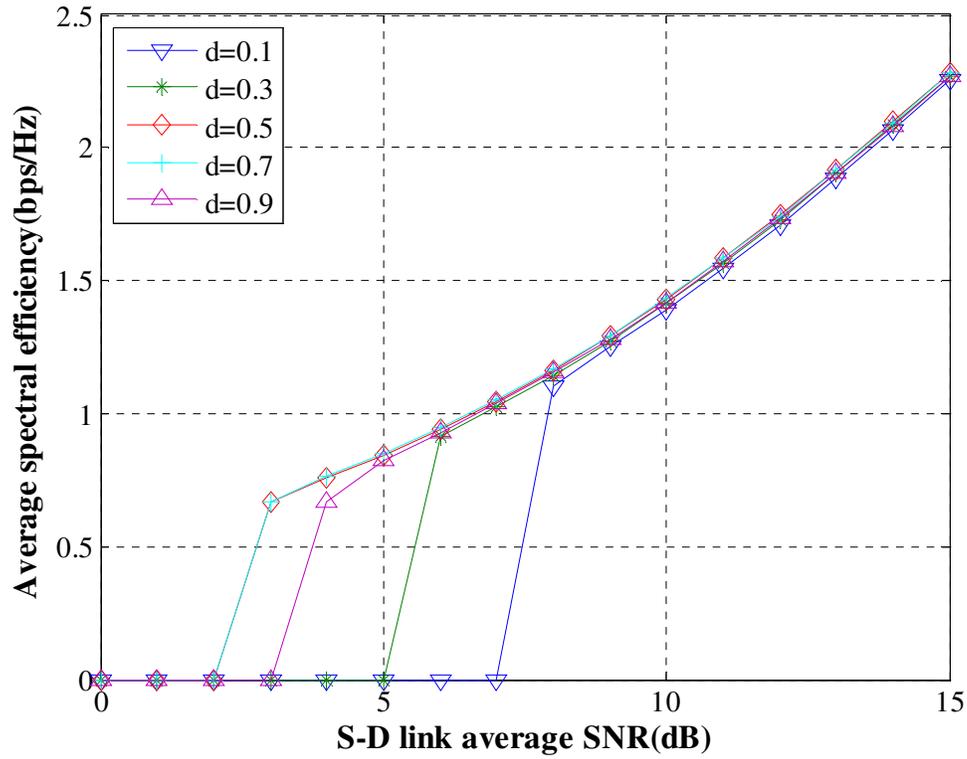
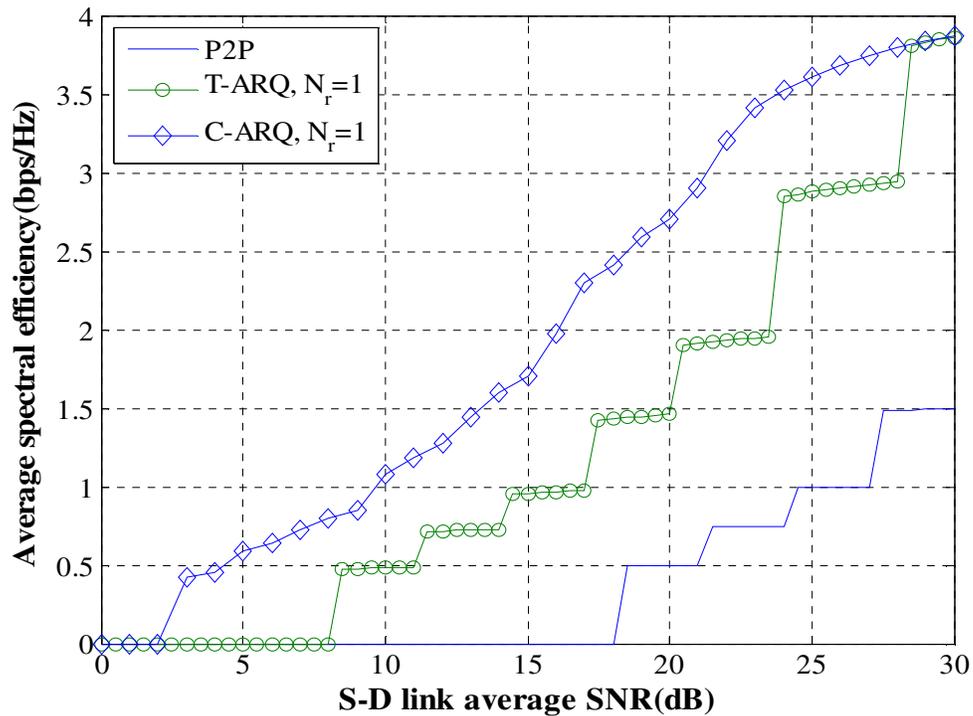


Fig. 5. Spectral efficiency of AMC with CARQ vs. the average SNR of S-D link for different conditions of S-R and R-D channels, $P_{loss} = 0.01$.



M. Mardani, J. S. Harsini, F. Lahouti, and B. Eliasi, "Link adaptive and QoS provisioning Cooperative ARQ - Applications to Relay Assisted Land Mobile Satellite Communications," *To Appear in IEEE Transactions on Vehicular Technology*, 2011.

Fig. 6. Spectral efficiency comparison of optimized fixed rate C-ARQ and T-ARQ schemes, $d = 0.5$, $P_{loss} = 0.01$.

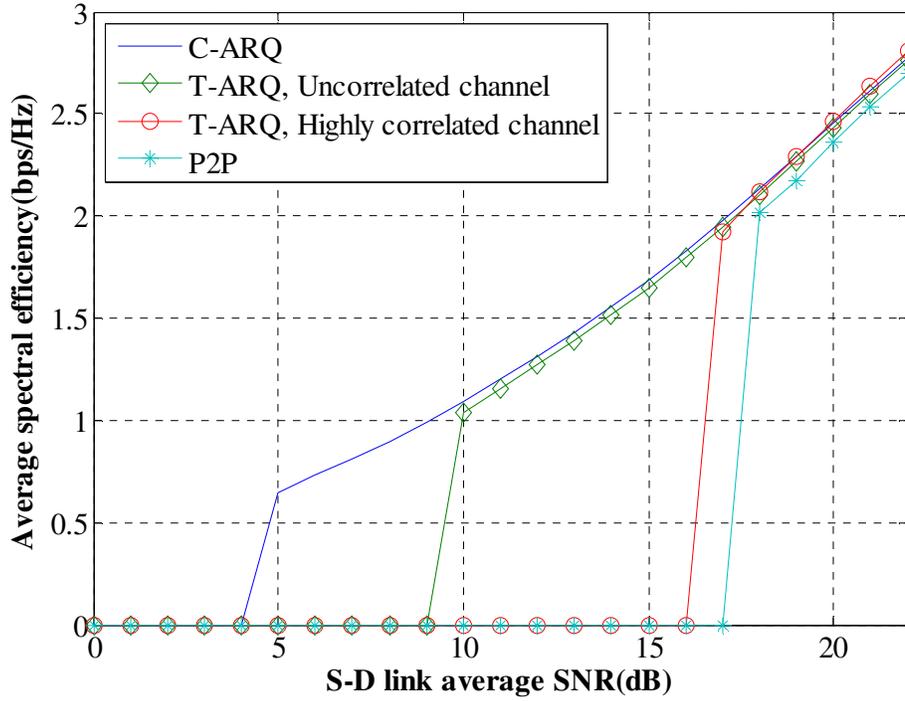


Fig. 7. Spectral efficiency vs. average SNR of S-D channel for joint C-ARQ and AMC, and AMC with/without T-ARQ schemes for LMSC. The parameters are $N_r = 1$, $d = 0.25$, $P_{loss} = 0.05$.

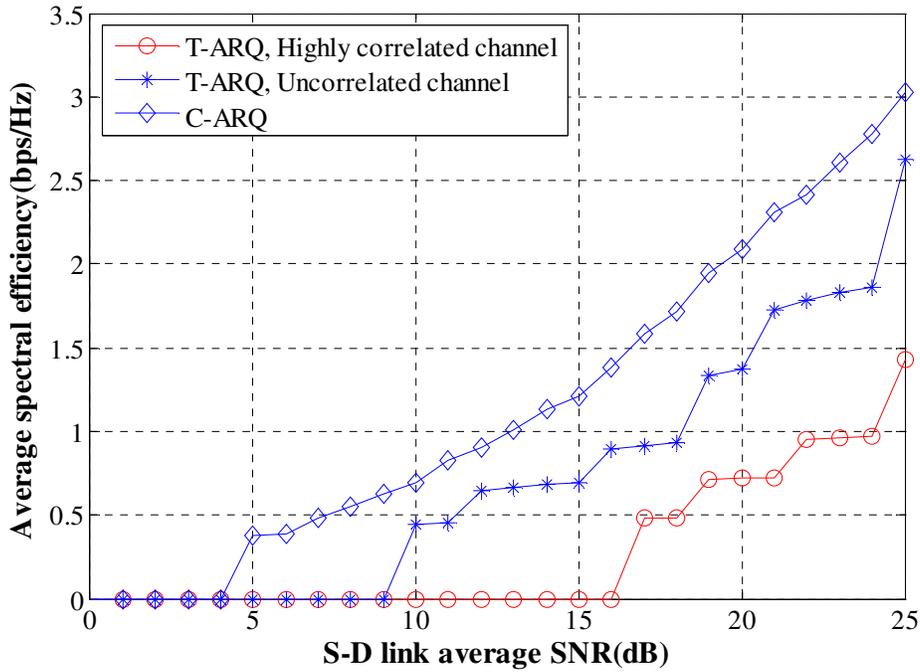


Fig. 8. Spectral efficiency comparison of optimized fixed rate C-ARQ and T-ARQ schemes in LMSC, $N_r = 1$, $d = 0.25$, $P_{loss} = 0.05$.

M. Mardani, J. S. Harsini, F. Lahouti, and B. Eliasi, "Link adaptive and QoS provisioning Cooperative ARQ - Applications to Relay Assisted Land Mobile Satellite Communications," *To Appear in IEEE Transactions on Vehicular Technology*, 2011.

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