Adaptive Modulation and Coding for Dual-Hop Transmission Systems with Regenerative Relaying

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***Abstract*—We consider the problem of performing adaptive modulation and coding (AMC) in dual-hop transmission systems with regenerative relaying. In particular, we consider a scenario where the AMC on both hops is done independently of each other, thus requiring a potential buffering of data packets at the relay station before they can be forwarded to the actual destination. In this regard, we propose that both the current channel conditions as well as the current buffer filling level are taken into account in the AMC mode selection, so that buffer overflows at the relay station can be completely avoided. We thoroughly analyze our scheme by means of a finite-state Markov model, based on which we derive various different performance measures, such as the average transmission efficiency or the average transmission delay.**

I. Introduction

Adaptive modulation and coding (AMC) represents a key technology for coping with the detrimental effects of multipath fading in wireless communication systems [1]. The basic idea of AMC is to adjust the used modulation scheme and code rate to the current channel conditions such that a modulation and coding scheme (MCS) with high spectral efficiency is chosen if the channel conditions are rather good whereas only little data is transmitted if the channel conditions are relatively poor. For conventional point-to-point links, AMC has been extensively studied in literature in recent years (see for example [1]–[4] and references therein). However, for more general multihop systems, the design and application of efficient AMC schemes still remains a widely untouched yet important and interesting research area. In such multihop systems, the data transmission between a source and the corresponding destination node is realized on a hop-by-hop basis via one or multiple intermediate relay stations [5]. By properly placing/selecting these relay stations, the average channel conditions on all hops can become much better than the average channel conditions on the direct link between source and destination, thus facilitating significant performance gains. For that reason, multihop transmission will play a crucial role for achieving rather high data rates in future wireless communication systems [5]–[7].

In this paper, we propose and analyze an approach for performing AMC in dual-hop transmission systems with one regenerative relay station. In this regard, we consider the case where the AMC on both hops is performed independently of each other, for which reason a buffering of packets at the relay station may be required, namely if not all packets transmitted by the source can be immediately forwarded again by the relay on the next hop. Furthermore, we adopt a cross-layer approach by taking into account both the fading channel conditions as well as the buffer filling level at the relay station during the AMC mode selection. We thoroughly analyze the performance of our scheme by means of a finite-state Markov chain model of our system, based on which we derive a wide variety of different performance measures, which are all given in closed-form for the case of Nakagami-m fading on both hops.

II. System and Channel Model

We consider a dual-hop transmission system, where the data transmission from a source node S to a destination node D is realized on a hop-by-hop basis via an intermediate relay station R operating in the well-known decode-and-forward mode [8]. In this regard, every end-to-end transmission interval is split into two different time slots of equal length. During the first phase, the source takes several data packets of equal size out of its input buffer, encodes and modulates the corresponding bits and transmits them to the relay station. The relay then tries to demodulate and decode the received signals and puts the successfully recovered packets into a buffer, which can accommodate at most L_{max} packets. Packets which could not be successfully decoded, in contrast, simply are dropped. During the second phase, the relay takes a certain number of packets out of this buffer, encodes and modulates them appropriately and eventually forwards them to the actual destination.

We assume that AMC is performed independently on both hops, where the number of packets that might be transmitted within a certain time slot depends on the selected MCS. As a concrete example, we consider as in [9] $N = 5$ different MCSs as given by Table I and we assume that each transmitted packet is encoded separately. As can be seen from Table I, the achievable rate with the i-th mode is greater than or equal to i times the rate of the first mode. Assuming for simplicity that with the first mode exactly one packet may be transmitted during one time slot, we consequently can transmit a maximum number of i packets if the i-th MCS is selected.

For the selection of an appropriate MCS on the S-R link, the relay first of all compares—similar to conventional AMC for single-hop systems [1], [2]—the instantaneous SNR γ_1 of the S-R link to a certain set of precalculated switching thresholds $\vartheta_{1,k}$ ($k = 0, \ldots, N+1$), where the k-th AMC mode could be

TABLE I
AVAILABLE MODULATION AND CODING SCHEMES

	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**
Modulation	BPSK	QPSK	QPSK	16-QAM	16-QAM
Code rate	1/2	1/2	3/4	9/16	3/4
Rate (bps)	0.50	1.00	1.50	2.25	3.00
a_i	274.72	90.25	67.61	50.12	53.39
g_i	7.99	3.49	1.68	0.66	0.37
γ_{T_i} (dB)	-1.533	1.094	3.972	7.702	10.249

used for the transmission if $\vartheta_{1,k} \leq \gamma_1 < \vartheta_{1,k+1}$. However, it might be the case that the number of packets that may be transmitted with this MCS exceeds the number of free slots in the relay buffer, thus causing a potential buffer overflow. If this happens, the relay therefore requests a lower-order MCS such that the number of transmitted packets is equal to the number of free slots in the relay buffer. Likewise, for the adaptation on the R-D link, the destination compares the corresponding SNR γ_2 to another set of switching thresholds $\vartheta_{2,k}$ ($k = 0, \ldots, N+1$) and feeds the index of the associated MCS back to the relay. Here, it might happen that actually more packets might be transmitted on the R-D link than are available in the buffer, in which case the chosen MCS is adjusted appropriately as well.

In the following, we always assume that the source has always packets to transmit, that $L_{\max} \geq N$, i.e., that the relay buffer can accommodate at least as many as might be transmitted at most during one time interval, and that we have zero-delay error-free feedback channels. Besides, the AMC switching thresholds $\vartheta_{i,k}$ for determining which MCS is supported for a certain SNR γ_i generally might be chosen differently for both hops. In the following, this is done in such a way that a certain target packet error rate (PER) is not exceeded. Using the standard PER approximation [4]

$$\mathrm{P}_{e,i}(\gamma) = \begin{cases} 1, & \text{for } 0 < \gamma < \gamma_{T_i} \\ a_i \exp(-g_i\,\gamma), & \text{for } \gamma \geq \gamma_{T_i} \end{cases}, \qquad (1)$$

with a_i, g_i and γ_{T_i} as given by Table I, we can readily determine the minimum SNR that is required such that with the k-th MCS a given target PER $P_{\text{target,i}}$ is not exceeded as $\vartheta_{i,k} = \frac{1}{g_k} \ln\left(a_k/P_{\text{target,i}}\right)$. In order to facilitate a unified analysis, we always set $\vartheta_{i,0} = 0$ as well as $\vartheta_{i,N+1} = \infty$ in the following, where the transmission is suspended if $\vartheta_{i,0} \leq \gamma_i < \vartheta_{i,1}$. Finally, we assume that both hops are subject to independent flat Nakagami-m block-fading with fading parameters m_1 and m_2 and average SNRs $\bar{\gamma}_1$ and $\bar{\gamma}_2$, respectively. Hence, the probability density function of the SNR γ_i is given by

$$p_{\gamma_i}(\gamma) = \frac{m_i^{m_i}\,\gamma^{m_i-1}}{\bar{\gamma}_i^{m_i}\,\Gamma(m_i)} \exp\left(-\frac{m_i\,\gamma}{\bar{\gamma}_i}\right), \qquad \gamma \geq 0 \qquad (2)$$

with $\Gamma(\cdot)$ as the well-known gamma function [10] and likewise the corresponding cumulative distribution function by

$$F_{\gamma_i}(\gamma) = 1 - \frac{\Gamma\left(m_i, \frac{m_i\,\gamma}{\bar{\gamma}_i}\right)}{\Gamma(m_i)}, \qquad \gamma \geq 0 \qquad (3)$$

with $\Gamma(\cdot,\cdot)$ as the upper incomplete gamma function [10].

III. FINITE-STATE MARKOV CHAIN MODEL

For analyzing the performance of our system, we develop a finite-state Markov chain model with $L_{\max}+1$ states, where each state is associated with a certain number of packets in the relay buffer, i.e., if the Markov chain is in the i-th state ($0 \leq i \leq L_{\max}$), this corresponds to the case where the relay buffer currently holds i packets. In this regard, we always consider the number of packets in the buffer after the transmission from S to R, but the alternative case where the number of packets in the buffer after the transmission from R to D is considered basically could be treated in exactly the same way.

In general, the transition probability $p_{i,j}$ that the Markov chain changes from state i to state j corresponds to the probability that the relay first of all forwards k packets ($0 \leq k \leq \min\{N, i\}$) to the destination provided that in total i packets are available while at the same time after the transmission from the source to the relay exactly $j-i+k$ are put into the buffer again given that after the forwarding of packets from R to D there are $L_{\max}-i+k$ free slots for storing additional packets. Exploiting the assumed independence of the two hops and denoting the probabilities of the aforementioned two events by $q_{k,i}$ and $r_{j-i+k,L_{\max}-i+k}$, respectively, we generally can express the transition probabilities $p_{i,j}$ as

$$p_{i,j} = \sum_{k=0}^{\min\{N,i\}} q_{k,i}\; r_{j-i+k,L_{\max}-i+k}. \qquad (4)$$

Clearly, if $k \leq \min\{N, i\} < i$, i.e., if not all packets that are currently stored in the buffer are forwarded, $q_{k,i}$ simply corresponds to the probability that the instantaneous SNR γ_2 on the R-D link falls into the k-th bin. If in contrast $k = i \leq N$, i.e., if all packets in the buffer are forwarded, $q_{k,i}$ corresponds to the probability that the R-D link is good enough so that *at least* k packets might be transmitted. Hence, we directly obtain

$$q_{k,i} = \begin{cases} F_{\gamma_2}(\vartheta_{2,k+1}) - F_{\gamma_2}(\vartheta_{2,k}), & \text{if } k < i \\ 1 - F_{\gamma_2}(\vartheta_{2,k}), & \text{if } k = i \\ 0, & \text{if } k > i \end{cases}, \qquad (5)$$

with $F_{\gamma_2}(\gamma)$ according to (3). The probability $r_{m,n}$ that exactly m packets are put into the buffer given that n slots are free, on the other hand, can easily be shown to be given by

$$r_{m,n} = \sum_{\nu=m}^{\phi_n} t_{m,\nu,n}, \qquad (6)$$

where we have introduced for brevity the short-hand notation

$$\phi_n = \min\{N, n\} \qquad (7)$$

and where $t_{m,\nu,n}$ denotes the joint probability that the source transmits ν packets given that there are n available slots in the relay buffer while the relay successfully decodes exactly m out of these ν packets. Clearly, for $\nu < n$, the transmission of ν packets requires that $\vartheta_{1,\nu} \leq \gamma_1 < \vartheta_{1,\nu+1}$ whereas for $\nu = n$ we necessarily have $\gamma_1 \geq \vartheta_{1,\nu}$ since even if the channel would be good enough to support a higher AMC mode, still at most only ν packets can be transmitted because otherwise a buffer overflow might occur. Consequently, we readily obtain

$$t_{m,\nu,n} = \begin{cases} \binom{\nu}{m} \int_{\vartheta_{1,\nu}}^{\vartheta_{1,\nu+1}} (1 - P_{e,\nu}(\gamma))^m \\ \qquad \times P_{e,\nu}(\gamma)^{\nu-m}\, p_{\gamma_1}(\gamma)\, d\gamma, & \nu < \phi_n \\ \binom{\phi_n}{m} \int_{\vartheta_{1,\nu}}^{\infty} (1 - P_{e,\phi_n}(\gamma))^m \\ \qquad \times P_{e,\phi_n}(\gamma)^{\phi_n - m}\, p_{\gamma_1}(\gamma)\, d\gamma, & \nu = \phi_n \\ 0 & \nu > \phi_n \end{cases}. \quad (8)$$

With the PER expressions according to (1) and by making use of the binomial theorem, it can be shown that

$$\begin{aligned}(1 - P_{e,\nu}(\gamma))^m\, P_{e,\nu}(\gamma)^{\nu-m} \\ = \sum_{\eta=0}^{m} \binom{m}{\eta} (-1)^\eta\, a_\nu^{\eta+\nu-m} \exp\left(-g_\nu\, \gamma\, (\eta + \nu - m)\right). \quad (9)\end{aligned}$$

Plugging this term in (8), inserting the Nakagami-m fading pdf as given by (2) and making use of [10, eq. (3.381,3)] yields the closed-form expression for $t_{m,\nu,n}$ according to (10), which is given at the top of the next page. Combining (10) with (6), (5) and (4) then finally yields the desired closed-form expressions for the general transition probabilities of our Markov chain.

The steady-state distribution vector $\boldsymbol{\pi} = [\pi_0, \pi_1, \ldots, \pi_{L_{\text{max}}}]$, where π_ν denotes the steady-state probability that the Markov chain is in state ν, is generally given by the solution of the linear equation system $\boldsymbol{\pi}\,\mathbf{P} = \boldsymbol{\pi}$, subject to $\pi_i \geq 0\ \forall\ i$ as well as $\sum_{i=0}^{L_{\text{max}}} \pi_i = 1$, with $\mathbf{P}$ as the transition probability matrix with entries $p_{i,j}$. This solution can be determined by noting that $\boldsymbol{\pi}\,\mathbf{P} = \boldsymbol{\pi}$ actually is a standard eigenvalue problem with $\boldsymbol{\pi}$ as a left eigenvector of $\mathbf{P}$ associated with eigenvalue one and normalized such that all entries sum up to one. So to determine $\boldsymbol{\pi}$, we might perform an eigenvalue decomposition of $\mathbf{P}^T$ and denote the eigenvector associated with eigenvalue one as $\mathbf{v} = [v_0, \ldots, v_{L_{\text{max}}}]^T$. Then, $\boldsymbol{\pi}$ is simply given by $\boldsymbol{\pi} = \mathbf{v}/\sum_{n=0}^{L_{\text{max}}} v_n$.

Based on the steady-state probabilities π_ν or equivalently the probabilities that the number of packets in the buffer after the transmission from S to R is equal to ν, we also can easily determine the probabilities π'_ν that the number of packets in the buffer after the forwarding of packets from R to D is equal to ν. This is the case if before the transmission on the R-D link i packets were in the buffer and then $i - \nu$ packets have been forwarded. Hence, we can directly determine π'_ν as

$$\pi'_\nu = \sum_{i=\nu}^{\min\{L_{\text{max}},\nu+N\}} \pi_i\, q_{i-\nu,i}, \quad (11)$$

with $q_{i-\nu,i}$ according to (5).

IV. Performance Analysis

A. Average Buffer Filling Level

The average buffer filling level denotes the average number of packets stored in the relay buffer. In this regard, we have to distinguish between the situation right after the transmission from S to R and the one after the transmission from R to D. For the first case, we readily obtain $L_{\text{avg}} = \sum_{\nu=1}^{L_{\text{max}}} \pi_\nu\, \nu$ with π_ν as the steady-state probability and likewise we get for the second case $L'_{\text{avg}} = \sum_{\nu=1}^{L_{\text{max}}} \pi'_\nu\, \nu$, with π'_ν according to (11).

B. Average Transmission Efficiency

The average transmission efficiency is defined as the average number of *transmitted* packets during one transmission interval. Considering first of all the R-D link, we can say that the relay forwards k packets to the destination iff there are more than k packets in the buffer and $\vartheta_{2,k} \leq \gamma_2 < \vartheta_{2,k+1}$ or if there are exactly k packets in the buffer and $\gamma_2 \geq \vartheta_{2,k}$. Consequently, we readily obtain for the R-D link

$$\begin{aligned}\eta_{\text{r-d}} \;=\; & \sum_{i=1}^{N} i \left((F_{\gamma_2}(\vartheta_{2,i+1}) - F_{\gamma_2}(\vartheta_{2,i})) \sum_{\nu=i+1}^{L_{\text{max}}} \pi_\nu \right. \\ & \left. + \pi_i\, (1 - F_{\gamma_2}(\vartheta_{2,i})) \right). \quad (12)\end{aligned}$$

Likewise, on the S-R link the source transmits exactly k packets if either $\vartheta_{1,k} \leq \gamma_1 < \vartheta_{1,k+1}$ and the buffer can store more than k additional packets or if the buffer can store exactly k more packets and $\gamma_1 \geq \vartheta_{1,k}$. Hence, we get in this case

$$\eta_{\text{s-r}} = \sum_{i=1}^{N} i \sum_{k=0}^{L_{\text{max}}} w_{i,k}\, \pi'_{L_{\text{max}}-k}, \quad (13)$$

with $w_{\nu,n}$ as the probability that the source transmits ν packets provided that the buffer at the relay station can accommodate at most n packets, which can easily be shown to be given by

$$w_{\nu,n} = \begin{cases} F_{\gamma_1}(\vartheta_{1,\nu+1}) - F_{\gamma_1}(\vartheta_{1,\nu}), & \text{if } \nu < \phi_n \\ 1 - F_{\gamma_1}(\vartheta_{1,\nu}), & \text{if } \nu = \phi_n \\ 0, & \text{if } \nu > \phi_n \end{cases}, \quad (14)$$

with ϕ_n according to (7).

C. Average Packet Error Ratio

The average PER corresponds to the average number of erroneously decoded packets over the total number of transmitted packets. If on the R-D link i packets are transmitted, always the i-th AMC mode is used. This is the case if either more than i packets are available in the relay buffer and $\vartheta_{2,i} \leq \gamma_2 < \vartheta_{2,i+1}$, or if exactly i packets are in the buffer and $\gamma_2 \geq \vartheta_{2,i}$. Hence, we can conclude that generally

$$\begin{aligned}\overline{\text{PER}}_{\text{r-d}} = \frac{1}{\eta_{\text{r-d}}} \sum_{i=1}^{N} i \left(\int_{\vartheta_{2,i}}^{\vartheta_{2,i+1}} P_{e,i}(\gamma)\, p_{\gamma_2}(\gamma)\, d\gamma \sum_{\nu=i+1}^{L_{\text{max}}} \pi_\nu \right. \\ \left. + \pi_i \int_{\vartheta_{2,i}}^{\infty} P_{e,i}(\gamma)\, p_{\gamma_2}(\gamma)\, d\gamma \right), \quad (15)\end{aligned}$$

which reduces with the PER expression according to (1) as well as the Nakagami-m fading pdf as given by (2) to

$$\begin{aligned}\overline{\text{PER}}_{\text{r-d}} = \frac{1}{\eta_{\text{r-d}}} \sum_{i=1}^{N} \frac{i\, a_i\, m_2^{m_2}}{(m_2 + \bar{\gamma}_2\, g_i)^{m_2}\, \Gamma(m_2)} \\ \times \left[\left[\Gamma\left(m_2, \left(\tfrac{m_2}{\bar{\gamma}_2} + g_i\right) \vartheta_{2,i}\right) - \Gamma\left(m_2, \left(\tfrac{m_2}{\bar{\gamma}_2} + g_i\right) \vartheta_{2,i+1}\right) \right] \right. \\ \left. \times \sum_{\nu=i+1}^{L_{\text{max}}} \pi_\nu + \pi_i\, \Gamma\left(m_2, \left(\tfrac{m_2}{\bar{\gamma}_2} + g_i\right) \vartheta_{2,i}\right) \right], \quad (16)\end{aligned}$$

where we used [10, eq. (3.381,3)] again and with $\eta_{\text{r-d}}$ according to (12). On the S-R link, in contrast, the i-th mode is chosen if

$$t_{m,\nu,n} = \begin{cases} \frac{m_1^{m_1}}{\bar{\gamma}_1^{m_1}\,\Gamma(m_1)} \binom{\nu}{m} \sum_{\eta=0}^{m} \frac{\binom{m}{\eta}(-1)^{\eta}\, a_{\nu}^{\eta+\nu-m}}{\left(\frac{m_1}{\bar{\gamma}_1}+g_{\nu}\,(\eta+\nu-m)\right)^{m_1}} & \\ \times\left[\Gamma\left(m_1,\left(\frac{m_1}{\bar{\gamma}_1}+g_{\nu}\,(\eta+\nu-m)\right)\vartheta_{1,\nu}\right)-\Gamma\left(m_1,\left(\frac{m_1}{\bar{\gamma}_1}+g_{\nu}\,(\eta+\nu-m)\right)\vartheta_{1,\nu+1}\right)\right] & \nu<\phi_n \\ \frac{m_1^{m_1}}{\bar{\gamma}_1^{m_1}\,\Gamma(m_1)} \sum_{\eta=0}^{m}\binom{\phi_n}{m}\binom{m}{\eta}\frac{(-1)^{\eta}\, a_{\phi_n}^{\eta+\phi_n-m}}{\left(\frac{m_1}{\bar{\gamma}_1}+g_{\phi_n}\,(\eta+\phi_n-m)\right)^{m_1}}\,\Gamma\left(m_1,\left(\frac{m_1}{\bar{\gamma}_1}+g_{\phi_n}\,(\eta+\phi_n-m)\right)\vartheta_{1,\phi_n}\right) & \nu=\phi_n \\ 0 & \nu>\phi_n \end{cases} \quad (10)$$

either more than i slots in the buffer are free and $\vartheta_{1,i} \leq \gamma_1 < \vartheta_{1,i+1}$ or if exactly i slots are free and $\gamma_1 \geq \vartheta_{1,i}$. Hence, the average PER can be determined in this case as

$$\overline{\text{PER}}_{\text{s-r}} = \frac{1}{\eta_{\text{s-r}}} \sum_{i=1}^{N} i \left(\int_{\vartheta_{1,i}}^{\vartheta_{1,i+1}} P_{e,i}(\gamma)\, p_{\gamma_1}(\gamma)\, d\gamma \sum_{\nu=0}^{L_{\max}-i-1} \pi'_{\nu} + \pi'_{L_{\max}-i} \int_{\vartheta_{1,i}}^{\infty} P_{e,i}(\gamma)\, p_{\gamma_1}(\gamma)\, d\gamma \right). \quad (17)$$

Considering as a concrete example the important case of Nakagami-m fading on both hops again as well as the PER expression according to (1), we can derive similarly to (16) an analytical closed-form expression for $\overline{\text{PER}}_{\text{s-r}}$ by making use of [10, eq. (3.381,3)], which, however, is not explicitly given here due to space constraints.

D. Average Transmission Delay

The average transmission delay Δ_{delay} is defined as the average delay a packet received by the destination has experienced since its transmission by the source. Hence, it simply corresponds to the average waiting time in the relay buffer plus one additional time interval for the actual packet transmission itself. Capitalizing on Little's well-known theorem [11], we hence obtain for Δ_{delay} (in end-to-end transmission intervals)

$$\Delta_{\text{delay}} = \frac{L'_{\text{avg}}}{\lambda} + 1, \quad (18)$$

where λ denotes the average arrival rate corresponding to the average number of successfully decoded packets at the relay station, which can be easily determined as

$$\lambda = \eta_{\text{s-r}} \left(1 - \overline{\text{PER}}_{\text{s-r}}\right), \quad (19)$$

with $\eta_{\text{s-r}}$ and $\overline{\text{PER}}_{\text{s-r}}$ according to (13) and (17), respectively. Besides, L'_{avg} denotes the average buffer level *as seen by an outside observer*, given by the average buffer level after the transmission from R to D as determined in Section IV-A.

E. Average Packet Loss Rate

The average packet loss rate is defined as the average number of packets transmitted by the source that are dropped at the relay station or the destination due to a packet error over the total average number of packets transmitted by the source. It can easily be seen that it generally can be determined as

$$P_{\text{loss}} = 1 - \frac{\eta_{\text{r-d}} \left(1 - \overline{\text{PER}}_{\text{r-d}}\right)}{\eta_{\text{s-r}}}, \quad (20)$$

with $\eta_{\text{r-d}}$ according to (12) and $\overline{\text{PER}}_{\text{r-d}}$ as well as $\eta_{\text{s-r}}$ according to (16) and (13), respectively.

V. Numerical Results

Fig. 1 depicts the steady-state probabilities of the various buffer filling levels after the transmission from S to R for a buffer size of $L_{\max}$ = 8 and different average SNRs, which are assumed to be always the same on both hops. As can be seen, with increasing SNR the probability that there are less than N = 5 packets in the buffer is approaching zero. This is reasonable since with very good channel conditions on the S-R link basically always the spectrally most efficient MCS is chosen, with which exactly N = 5 packets can be transmitted during one time interval. However, the probability that there are always exactly N packets in the buffer is not approaching one, even though one could argue that also on the R-D link basically always the highest order MCS might be chosen in that case, so that all received packets can be immediately forwarded. This is because for all finite SNRs there is still a small probability that another AMC mode has to be used and if this happens once on the R-D link, packets are accumulated in the buffer and only reduced again if the S-R link is also getting very poor, so that less than N packets are delivered from the source. Since this happens very rarely as well, a situation with more than N packets in the buffer represents a stable state with a non-zero steady-state probability.

Fig. 2 shows the average end-to-end transmission efficiency—which is equal to the transmission efficiency $\eta_{\text{r-d}}$ on the R-D link—as well as the average packet loss rate for different buffer sizes and average SNRs. Clearly, with increasing buffer size the transmission efficiency can be slightly increased since the relay can store more packets and therefore the probability that it runs out of data is decreased. At the same time, however, the average packet loss rate slightly increases with increasing $L_{\max}$, but the differences are generally rather small. The reason for this is that with a small buffer, it sometimes happens that a lower-order MCS has to be used than what would be acceptable if only the current channels were considered since otherwise a buffer overflow would occur or since the relay has not enough packets to transmit. Therefore, the probability that the packets are correctly decoded increases, thus also reducing the packet loss rate.

Finally, Fig. 3 illustrates the average transmission delay as a function of the average SNR for different buffer sizes and two different PER targets. Clearly, with increasing SNR the delay can be significantly reduced because the number of packets transmitted during one time interval generally increases. However, at a certain point the curves flatten out, where the limiting value is dependent on the buffer size. This is due to the fact that—as outlined before—in the high SNR regime there is always a non-zero probability that more than N packets are accumulated in the relay buffer. Hence, it is not always possible to forward all packets received from the source in the same time interval, even if on the R-D link almost always the highest MCS is selected. Clearly, with larger buffers the probability that packets are accumulated at the relay station and the number of accumulated packets is increasing as well and therefore the delay floor is an increasing function of $L_{\max}$. Finally, it can be seen that with a tighter PER constraint the delay generally increases also, because at least for low to moderate average SNRs in this case fewer packets are transmitted on average than with a rather loose PER constraint.

VI. Conclusion

We have proposed and thoroughly analyzed an approach for performing AMC in dual-hop transmission systems with regenerative relaying, where the AMC is done independently on both hops. In this regard, both the current channel conditions and the buffer filling level are taken into account for selecting an appropriate MCS, so that buffer overflows at the relay station can be completely avoided. Based on a finite-state Markov chain model of our system, we have derived a variety of different key performance indicators, which were given in closed-form for the important case of Nakagami-m fading on both hops. Selected numerical results illustrated the performance of the proposed approach and particularly highlighted the impact of the buffer size at the relay station.

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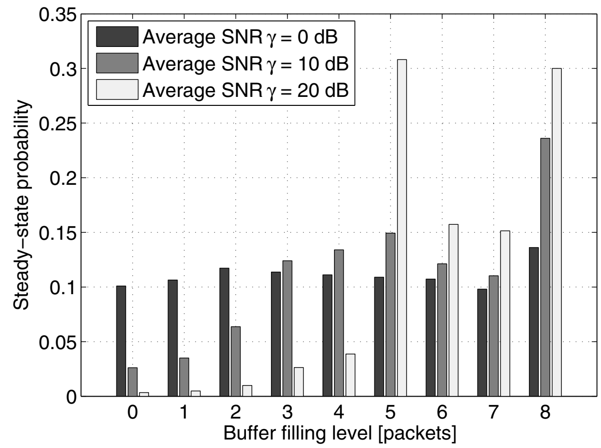

Fig. 1. Steady-state probabilities for the different buffer filling levels after the transmission from S to R for $\bar{\gamma}_1 = \bar{\gamma}_2 = \gamma$, Rayleigh-fading on both hops ($m_1 = m_2 = 1$), $L_{\max} = 8$, and $P_{\text{target},1} = P_{\text{target},2} = 0.1$.

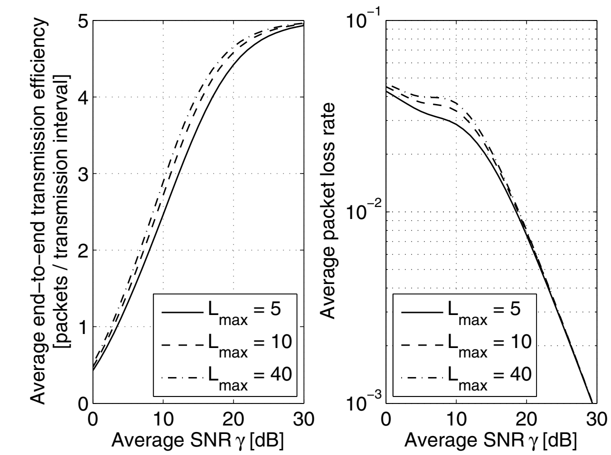

Fig. 2. Average end-to-end transmission efficiency and average packet loss rate for various buffer sizes as a function of the average SNR $\bar{\gamma}_1 = \bar{\gamma}_2 = \gamma$ with Rayleigh-fading on both hops and $P_{\text{target},1} = P_{\text{target},2} = 0.1$.

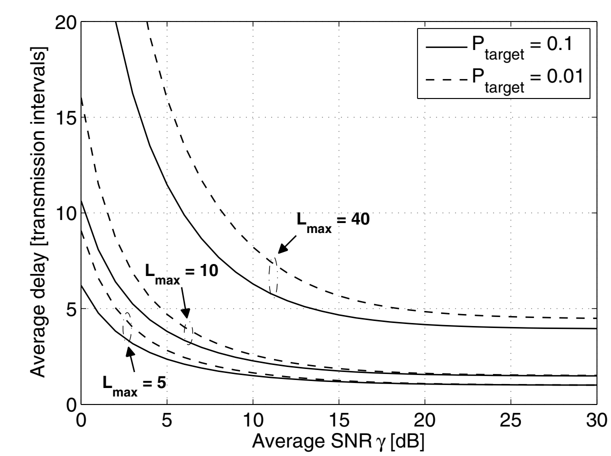

Fig. 3. Average end-to-end transmission delay for various buffer sizes as a function of the average SNR $\bar{\gamma}_1 = \bar{\gamma}_2 = \gamma$ with Rayleigh-fading on both hops and $P_{\text{target},1} = P_{\text{target},2} = P_{\text{target}}$.