Cross-Layer Design of Adaptive Network-Coded QAM Aided Truncated ARQ in Two-Way Relaying

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***Abstract*—As a promising technique, cooperative relaying has attracted more and more attention from academia and industry recently. In this paper, we investigate the scheme of Decode-and-Forward Two-way Relaying (DF-TWR) relying on a cross-layer design, which combines adaptive Network-coded Modulation (NCM) at the physical layer and truncated Automatic Repeat reQuest (ARQ) at the data link layer. The relay node utilizes Network-Coded Quadrature amplitude modulation (NC-QAM) where NCM imposes only a modest signal-to-noise ratio (SNR) degradation on the single-link QAM performance. Additionally, we derive the achievable spectral efficiency in closed-form for transmission over Rayleigh fading channels. It is shown that this combination of adaptive NC-QAM and truncated ARQ substantially improves the system's throughput compared to the schemes operating without ARQ.**

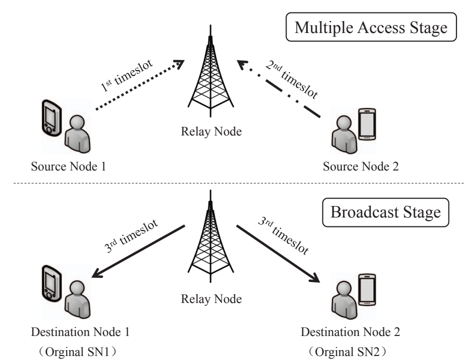

Fig. 1. System Model of DF-TWR (three timeslot)

I. Introduction

In wireless communications, cross-layer design is a promising technique which has substantially received research attention amongst both academics and industrial researchers [1–5]. In [1] and [2], a cross-layer scheme combining truncated ARQ with cooperative diversity was conceived for maximizing the attainable throughput by optimally choosing the packet length. Chen *et al.* presented a novel cross layer method for interference cancellation and network coding in [3]. Other seminal contributions were focused on the amalgamation of physical and link layer techniques in addition to adaptive modulation (AM), such as truncated ARQ [4, 5], where the number of retransmissions per packet is limited. The studies in [3] and [5] inspired us to intrinsically amalgamate the network coding (NC) technique with adaptive modulation for some communication scenarios.

The growing demand for wireless services has created the need for improving the spectral efficiency of wireless communications over fading channels. In the context of time-varying fading channels, adaptive modulation can be used for mitigating the fading effects and for maximizing the average spectral efficiency [6, 7], where the optimal modulation switching levels were found to maintain the target bit-error-ratio (BER) constraint stipulated. Constant-power and variable-rate adaptive modulation was combined with NCM for Decode-and-Forward Two-way Relaying (DF-TWR) in [8]. Furthermore, variable-rate and variable-power adaptive modulation amalgamated with NC-QAM was studied in [9]. These adaptive physical layer schemes motivated us to investigate the combination of this technique with higher-layer techniques, specific to the practical and useful scenario of DF-TWR, see Fig. 1. This scenario will be introduced in detail later.

Among a range of related studies on applying ARQ techniques to DF-TWR or NC [10–12], Hanzo *et al.* [10, 11] investigated Hybrid Automatic-Repeat-reQuest (HARQ) both in the single-relay and multiple-relay networks. The authors of [12] investigated broadcasting to multiple destinations over erasure channels. As a further advance from [5] and [9], we conceive a novel cross-layer design, namely truncated-ARQ-aided adaptive NC-QAM, which combines network coding and adaptive modulation at the physical layer with truncated-ARQ at the data link layer, for the sake of improving the attainable throughput of a DF-TWR network.

Against this background, especially the inspirational contributions of [5] and [9], we summarize some of the difference and difficulties of our research as follows.

1) *Peer-to-peer transmission vs Two-way Relay Channels.*

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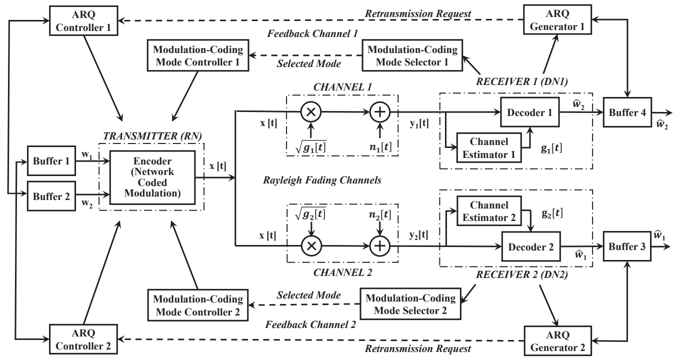

Fig. 2. Cross-layer channel model combining adaptive NC-QAM with ARQ for the downlink of DF-TWR

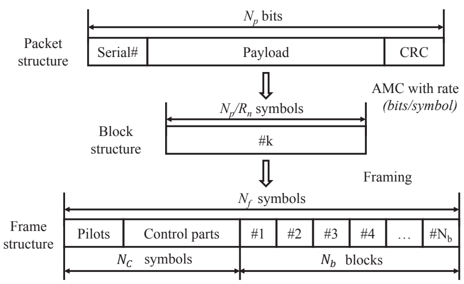

Fig. 3. The packet and frame structures[5]

In contrast to [5], we extend peer-to-peer transmission to a DF-TWR network, where the transmission strategy at the relay node (RN) has to simultaneously adapt to a pair of channel conditions, namely to the RN-Destination Node(DN) 1 and to the RN-DN2 channels.

2) *Cross-layer design for DF-TWR scenario*. Compared to [5], we extend the physical layer design to a cross-layer design. Therefore the optimization problem is quite different from those of [5] and [9].
3) *SNR-loss imposed by NC-QAM*. As detailed in [8] and [9], NC-QAM imposes a modest SNR-loss compared to a single QAM link, owing to two-way communications. Hence our transmission strategy is designed by directly taking into account this SNR-loss.

II. System and Channel Models

A three-time-slot DF-TWR consisting of a RN and two destination nodes is shown in Fig. 1. Two DNs intend to exchange their messages through the RN utilizing time-division technique. Based on Fig. 1, we conceive our cross-layer design for the downlink of the DF-TWR regime of Fig. 2. The processing unit of adaptive modulation at the physical layer are frames, while the processing unit of ARQ at the data link layer are packets [4]. The feedback information (channel state information (CSI) and the retransmission request signal) is feed back via different loops.

At the physical layer, multiple transmission modes are available. The modulation-coding mode selectors determine the modes based on CSIs, then the controllers update the transmission modes at the RN. We assumed that the RN has received the messages w_1 and w_2 from SN1 and SN2 without any error during the multiple access stage. Messages w_i will be processed using NCM method [8], then broadcasted to both DNs. Signal received at the DNs are denoted by $y_1[t]$ and $y_2[t]$ (t denotes the time instant). Since the channel is assumed to be stationary and ergodic, we could omit the parameter t of $y_1[t]$ and $y_2[t]$, yielding

$$y_i = h_i x + Z_i, i = 1, 2, \tag{1}$$

where h_i denotes the time-varying gain, with $|h_i|^2 = g_i$, while Z_i denotes the noise density of the additive white Gaussian noise (AWGN). At both DNs, coherent demodulation and NCM decoding method is used.

At the data link layer, truncated ARQ protocols are implemented. The ARQ generators and controllers arrange retransmission of the requested packet stored in the buffers. More details of ARQ protocols adopted in this scheme will be clarified in Section III. Since ARQ is used at the data link layer, we deal with frame-by-frame transmission at the physical layer, with each frame composed of a number of packets. Both the packet and frame structures used by our ARQ protocols are shown in Fig. 3[5]. Each frame contains N_f number of symbols, while each packet contains N_p bits. The N_p bits include both the packet index, as well as the payload and the cyclic redundancy check (CRC) bits facilitating error detection. If we choose a transmit rate of R_n, then each packet is mapped to a symbol-block containing N_p/R_n symbols.

For convenience in subsequent discussion, we define instantaneous SNRs $\gamma_i = \bar{S}g_i/(N_0B)$, with mean $\bar{\gamma}_i = \bar{S}\bar{g}_i/(N_0B)$ and distribution $p_i(\gamma_i)$, where g_i represents the channel gains with mean $\bar{g}_i$, $\bar{S}$ the average transmit power, N_0 the power spectral density of the noise and B the bandwidth. Next we list the assumptions adopted in this paper.

A1) The channel is assumed to be a slowly-varying non-dispersive fading channel.
A2) Perfect CSI is available both at DN1 and DN2 with the aid of training-based channel estimation. The feedback loops are error free and impose no delay, as in [7].
A3) Sufficiently reliable CRC codes are used for perfect error detection.

III. Combining Adaptive NC-QAM with Truncated ARQ

In this section, we develop our cross-layer design, which combines adaptive NC-QAM at the physical layer with truncated ARQ at the data link layer. To conceive the truncated-ARQ aided adaptive NC-QAM scheme, we have to consider three intriguing constraints.

B1) NC-QAM suffers from a modest SNR-loss due to the direct current (DC) bias of two-way communications, as detailed in [8], which is given by

$$\lambda_i = \begin{cases} \frac{1-M_i{}^{-1}}{1-M_1{}^{-1}}, if \ \ M_1 \geq M_2 \geq 2, i = 1, 2 \\ \frac{1-M_i{}^{-1}}{1-M_2{}^{-1}}, if \ \ M_2 \geq M_1 \geq 2, i = 1, 2, \end{cases} \tag{2}$$

with M_1 and M_2 denoting the constellation sizes.

B2) The maximum tolerable number of retransmissions per packet for the downlinks are $N_{\gamma_i}^{\max}$. E. g., if the QoS requires a delay of less than 600 ms, while the average round trip delay is 100 ms, then we have $N_{\gamma_i}^{\max} \leq 6$.

B3) The probability of packet loss after $N_{\gamma_i}^{\max}$ retransmissions is no higher than $P_{i,loss}$. If we constrain the instantaneous PERs for the RN-DNs links to be no higher than $P_0^{N_{\gamma_i}^{\max}}$, then we have

$$P_0^{N_{\gamma_i}^{\max}+1} \leq P_{i,loss} := P_{i,target}, i = 1, 2. \tag{3}$$

A. Adaptive NC-QAM Design at the Physical Layer

We first develop the adaptive NC-QAM design based on the relationship of BER and PER at the physical layer. According to [5], the PER expressions of uncoded QAM are given by

$$PER_i = 1 - (1 - BER_i)^{N_{p_i}}, i = 1, 2, \tag{4}$$

where N_{p_i} is the number of bits contained in a packet. As for coded QAM, the related PER and BER relationships are obtained by Monte-Carlo simulations [4].

The modulation-mode activation algorithm [5] is the core of the design, when combining AM with ARQ. We pursue a similar curve-fitting based approach by letting

$$PER_{i,n}(\gamma) \approx \begin{cases} 1, & if \;\; 0 < \gamma_i < \gamma_{i,pn} \\ a_{i,n} \exp(-g_{i,n} \lambda_i \gamma_i), & if \; \gamma_i \geq \gamma_{i,pn} \end{cases}, i = 1, 2, \tag{5}$$

where $a_{i,n}$, $g_{i,n}$ and $r_{i,n}$ are the parameters of the AM mode n, each of which corresponding a specific constellation size (transmit rate). Eq. (5) can be rewritten as

$$\begin{cases} \gamma_{i,0} = 0 \\ \gamma_{i,n} = \frac{1}{\lambda_i g_{i,n}} \ln\left(\frac{a_{i,n}}{P_{i,target}}\right) \\ \gamma_{i,N_i+1} = +\infty, \end{cases} \tag{6}$$

where $i, n = 1, 2, ..., N_i, i = 1, 2$ denote the AM region subscripts for the two links. Therefore the boundaries of the AM modes for DN1 and DN2 are:

$$\mathcal{R}_{i,n} = \left[\lambda_i^{-1}\gamma_{i,n}, \lambda_i^{-1}\gamma_{i,n+1}\right), \tag{7}$$

where λ_i is given by Eq. (2) in B1). As in [5] and [7], we partition the total SNR ranges into $N_i + 1$ non-overlaping consecutive intervals, with boundaries denoted by $\mathcal{R}_{i,n}$, where

$$\text{AM mode } n \text{ is chosen, when } \gamma_i \in \mathcal{R}_{i,n}. \tag{8}$$

B. NC-QAM Amalgamated with Truncated ARQ

The choice of the appropriate ARQ protocols conceived for adaptive NC-QAM crucially hinges on striking a compelling tradeoff between the system's throughput, latency, energy and design complexity. We then conceive the Selective Repeat (SR)-ARQ protocol for AM at the link layer. The NC-based SR-ARQ transmission mechanism at the data link layer is shown in Fig. 4, where the NC operation is carried out at the RN, while the ARQ operation at the DNs. When SR-ARQ protocol is adopted, buffers are needed, as shown in Fig. 2. A detailed transmission flow example is given in Fig. 4, where

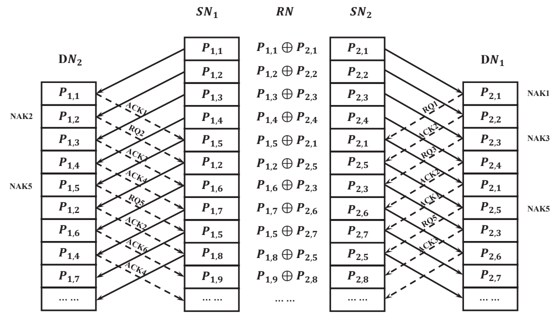

Fig. 4. Network coding (NC)-based SR-ARQ protocol

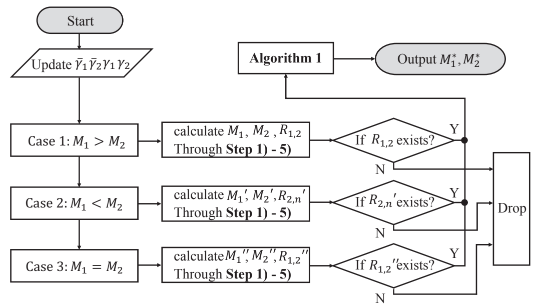

Fig. 5. Flow chart of selecting transmission modes

RN sends a continuous stream of merged packets. If there are any retransmission requests at either of the pair of DNs, e.g., owing to a negative acknowledgment (NAK) signal for $P_{2,3}$ at DN1, a retransmission request will be sent to the RN. Then packet $P_{2,3}$ will be resent at the time instant, when RN received the NAK signal.

We next detail the transmission strategy for the joint-optimization design.

1) Strategy of Selecting Constellations for Adaptive NC-QAM: The first step of combining adaptive NC-QAM with ARQ is to select the highest-throughput transmit modes (constellation sizes) of the different links. The reason for doing this is that we cannot be certain which links will the SNR-loss occur in. Since this performance loss will only exits at the link exhibiting the lower transmit rate [8, 9], there are only three cases to be discussed. The flow chart of selecting the constellation sizes of M_1 and M_2 is shown in Fig. 5, which is illustrated in the following steps:

Step 1: Initialize the parameters, which include the SNR γ_i, the average SNR $\bar{\gamma}_i$, the constellation sets M_1 and M_2.

Step 2: Case I: If $M_1 > M_2$, then we have $\lambda_1 = 1$ and $\lambda_2 = \left(1 - M_2^{-1}\right)/\left(1 - M_1^{-1}\right)$. In this case, we adopt the M_1 constellation for the RN-DN1 link and M_2 for RN-DN2 link. We denote the throughput of this scenario by

$$R_{1,2} = \omega_1 \log_2 M_1 + \omega_2 \log_2 M_2. \tag{9}$$

Step 3: Case II: If $M_1 < M_2$, then we have $\lambda_2 = 1$ and $\lambda_1 = \left(1 - M_1^{-1}\right)/\left(1 - M_2^{-1}\right)$. We denote the resultant throughput of this case as

$$R'_{1,2} = \omega_1 \log_2 M'_1 + \omega_2 \log_2 M'_2. \tag{10}$$

TABLE I

TRANSMISSION MODES AND ADJUSTMENT FOR M-ARY NC-QAM

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Modulation	4QAM	8QAM	16QAM	32QAM	64QAM	128QAM
Rate(bits/sym.)	2	3	4	5	6	7
$a_{i,n}$	111.5424	94.6210	84.7006	74.2778	66.8472	61.2536
$g_{i,n}$	0.5118	0.1709	0.1024	0.03943	0.02441	0.00969
$\gamma_{i,pn}$(dB)	9.6202	14.2669	16.3681	20.3630	22.2833	26.2752
E.g., $M_1 = 32$, then $M_2 \in \{4, 8, 16\}$ PER parameters with SNR-loss for the RN-DN2 link						
$a'_{2,n}$	111.2646	91.8151	87.4836			
$g'_{2,n}$	0.3969	0.1539	0.09941			
$\gamma'_{2,pn}$(dB)	10.7428	14.6550	16.4780			

Algorithm 1 Transmission Mode Selection Algorithm

Input: $\hat{\Re}$
Output: M_1^*, M_2^*
Initial: $R_{1,2}$, $R_{1,2}{'}$ or $R_{1,2}{''}$

1): Existence Judgement

- **If** $R_{1,2} \in \hat{\Re}$, $R_{1,2}{'} \in \hat{\Re}$ and $R_{1,2}{''} \in \hat{\Re}$
  - **If** $R_{1,2} \geq R_{1,2}{'}$ and $R_{1,2} \geq R_{1,2}{''}$, let $M_1^* = M_1$, $M_2^* = M_2$
  - **Else if** $R_{1,2}{'} \geq R_{1,2}$ and $R_{1,2}{'} \geq R_{1,2}{''}$, let $M_1^* = M_1{'}$, $M_2^* = M_2{'}$
  - **Else** let $M_1^* = M_1{''}$ and $M_2^* = M_2{''}$
- **Else** goto **2)**

2): Existence Judgement

- **If** $R_{1,2} \in \hat{\Re}$, $R_{1,2}{'} \in \hat{\Re}$ and $R_{1,2}{''} \notin \hat{\Re}$
  - **If** $R_{1,2} \geq R_{1,2}{'}$, let $M_1^* = M_1$ and $M_2^* = M_2$
  - **Else** let $M_1^* = M_1{'}$ and $M_2^* = M_2{'}$
- **Else** goto **3)**

3): Existence Judgement

- **If** $R_{1,2} \in \hat{\Re}$, $R_{1,2}{''} \in \hat{\Re}$ and $R_{1,2}{'} \notin \hat{\Re}$
  - **If** $R_{1,2} \geq R_{1,2}{''}$, let $M_1^* = M_1$ and $M_2^* = M_2$
  - **Else** let $M_1^* = M_1{''}$ and $M_2^* = M_2{''}$
- **Else** goto **4)**

4): Existence Judgement

- **If** $R_{1,2}{'} \in \hat{\Re}$, $R_{1,2}{''} \in \hat{\Re}$ and $R_{1,2} \notin \hat{\Re}$
  - **If** $R_{1,2}{'} \geq R_{1,2}{''}$, let $M_1^* = M_1'$ and $M_2^* = M_2'$
  - **Else** let $M_1^* = M_1{''}$ and $M_2^* = M_2{''}$
- **Else** goto **5)**

5): Existence Judgement

- **If** $R_{1,2} \in \hat{\Re}$, $R_{1,2}{'} \notin \hat{\Re}$ and $R_{1,2}{''} \notin \hat{\Re}$, let $M_1^* = M_1$ and $M_2^* = M_2$
- **Else if** $R_{1,2}{'} \in \hat{\Re}$, $R_{1,2}{'} \notin \hat{\Re}$ and $R_{1,2}{''} \notin \hat{\Re}$, let $M_1^* = M_1{'}$ and $M_2^* = M_2{'}$
- **Else** let $M_1^* = M_1{''}$ and $M_2^* = M_2{''}$

Step 4: Case III: If $M_1 = M_2$, we have $\lambda_1 = \lambda_2 = 1$. In this case, there is no SNR-loss, therefore we have

$$R''_{1,2} = \omega_1 \log_2 M''_1 + \omega_2 \log_2 M''_2. \tag{11}$$

Step 5: All possible cases were analyzed in the above three steps. However, for a given instantaneous SNR of γ_1 and γ_2, one or more cases maybe reasonable. Therefore, we propose **Algorithm 1** for determining the particular transmission modes for the corresponding nodes. If there are any changes in the instantaneous SNRs γ_1 and γ_2, go back to ***Step 1*** and recalculate the optimal transmission modes.

2) The Achievable Bandwidth-Efficiency: If the two links' transmission rates are different, there will be an SNR loss given a specific average throughput. It is hard to analyze the average bandwidth efficiency, because the transmission scheme is real-time AM scheme having a time-variant throughput. For M-ary QAM, the constellation size is generally larger than 4, therefore we may set the SNR-loss lower bound (suppose $M_1 > M_2$) as $\lambda_1 = \lambda_2$

$$\lambda_2 = \frac{1 - M_2^{-1}}{1 - M_1^{-1}} > 1 - \frac{1}{M_2} > \frac{3}{4}. \tag{12}$$

The upper bound can be set as $\lambda_1 = \lambda_2 = 1$, which indicates that there is no SNR loss. Upon setting both the upper bound and lower bound for the SNR-loss, we may view the pair of downlinks as two independent transmission links. Thus the bandwidth efficiency of NC-QAM can be obtained by the same approach, as for adaptive NC-QAM, yielding:

$$\bar{S}_{QAM}\left(N^{\max}_{\gamma_1,\gamma_2}\right) = \omega_1 \bar{S}\left(N^{\max}_{\gamma_1}\right) + \omega_2 \bar{S}\left(N^{\max}_{\gamma_2}\right), \tag{13}$$

where ω_i denotes the weighting factor of the RN-DN1 and RN-DN2 links, while $\bar{S}\left(N^{\max}_{\gamma_i}\right)$ is given by

$$\begin{aligned}\overline{S}\left(N^{\max}_{\gamma_i}\right) &= \frac{\overline{S}_{e_i,physical}}{\overline{N_i}\left(p_i, N^{\max}_{\gamma_i}\right)} \\ &= \frac{1}{\overline{N}\left(p_i, N^{\max}_{\gamma_i}\right)} \sum_{n=1}^{N_i} R_{i,n} \mathrm{Pr}_i\left(n\right), i = 1, 2,\end{aligned} \tag{14}$$

where $\bar{S}_{e_i,physical}$, $\overline{N_i}\left(p_i, N^{\max}_{\gamma_i}\right)$ and $\mathrm{Pr}_i\left(n\right)$ can be obtained from Eqs. (7)-(13) of [5].

IV. PERFORMANCE EVALUATION

In this section, we present our simulation and theoretical results to assess the attainable performance of the system studied.The corresponding parameters are listed here:

– *Rayleigh Fading distribution*: $p(\gamma_i)$ is given by

$$p\left(\gamma_i\right) = \frac{1}{\bar{\gamma}_i} \exp\left(-\frac{\gamma_i}{\bar{\gamma}_i}\right), i = 1, 2. \tag{15}$$

– *Packet length*: Similar to [5], we let $N_p = 1080$.

– *Delay constraints adhering to B2) and B3)*: Let $N_i^{\max}, i = 1, 2$ vary from 0 to 1, with $P_{i,loss} = 0.01$.

– *Average SNRs and constellation sets*: Let $\overline{\gamma_i} = [0, 1, ..., 30], i = 1, 2$ (in dB), $M_i \in \{4, 8, 16, 32, 64, 128\}$.

– *SNR-loss bounds adhering to B3)*: Let $\lambda_i = 1, i = 1, 2$ be the upper bound, while $\lambda_i = 3/4$ be the lower bound.

– *Weighting factors*: Let $\omega_i = 0.5, i = 1, 2$.

– *Equations*: Eqs. (12)-(15), include Eqs. (7)-(13) from [5].

Table I lists the PER fitting parameters $a_{i,n}$, $g_{i,n}$ and $\gamma_{i,pn}$ for uncoded adaptive NC-QAM. Let us briefly consider the special case of the SNR-loss for $M_1 = 32$ and $M_1 > M_2$ as shown in Fig. 6. In this case, we recalculate the PER-curve fitting parameters for the set $\mathcal{M}_\mathbf{2} = \{4, 8, 16\}$, with the adjusted parameters $a'_{2,n}$, $g'_{2,n}$ and $\gamma'_{2,pn}$ also listed in Table I. The dashed curves in Fig. 6 show the PER changes for the RN-DN2 link, compared to the PER curves drawn without SNR-loss in solid lines.

As shown in Fig. 6, the gaps between the curves recorded both with and without SNR-loss tend to become narrow upon reducing the difference between M_1 and M_2. This indicates that the performance loss decreases along with the decreasing the two links' rates. In Table I, the changes between $\gamma_{2,pn}$ and $\gamma'_{2,pn}$ also show the reason for the reduction of the average

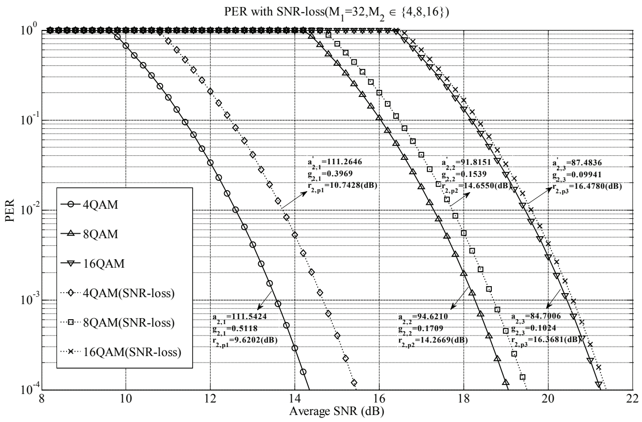

Fig. 6. PER change along with SNR-loss for RN-DN2 link (Tabel I)

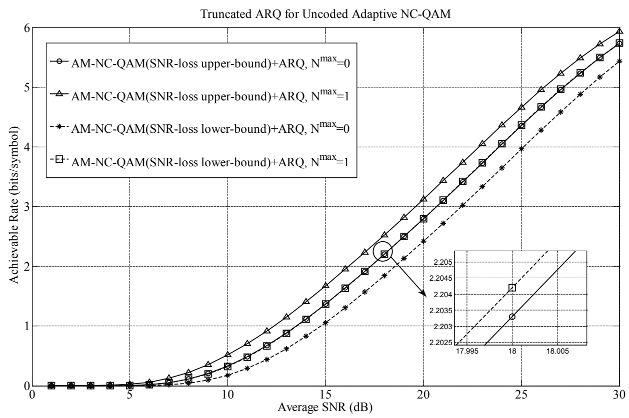

Fig. 7. Average spectral efficiency versus SNR for uncoded adaptive NC-QAM with truncated-ARQ

throughput, which is due to the fact that the integration interval in Eqs. (5) and (6) corresponding to the higher constellation sizes becomes smaller, compared to the integration range of Eq. (6) without SNR-loss.

In Figs. 7 and 8 we separately plot the average throughput for the uncoded and channel coded adaptive NC-QAM scheme. Several observations are worth discussing. Firstly, for the case of $N_i^{max} = 1, i = 1, 2$, the achievable rate curves associated with no SNR-loss (upper bound) tends to exceed that associated with the lower bound by about 0.25 b/transmitted symbol. Secondly, there are two curves close to each other, because we set the lower bound of the SNR-loss to be $\lambda_1 = \lambda_2 = 0.75$, which is approximately equal to the gains attained by the $N^{max} = 1$ truncated-ARQ mechanism. These numerical results indicate that our proposed adaptive NC-QAM associated with truncated-ARQ holds the potential of improving the throughput of our DF-TWR network. Furthermore, the SNR-loss imposed by the two-way links relying on different QAM modes remains modest.

V. Conclusions

In this paper, we proposed a cross-layer design method for inherently amalgamating truncated ARQ at the data-link layer with adaptive NC-QAM at the physical layer, which

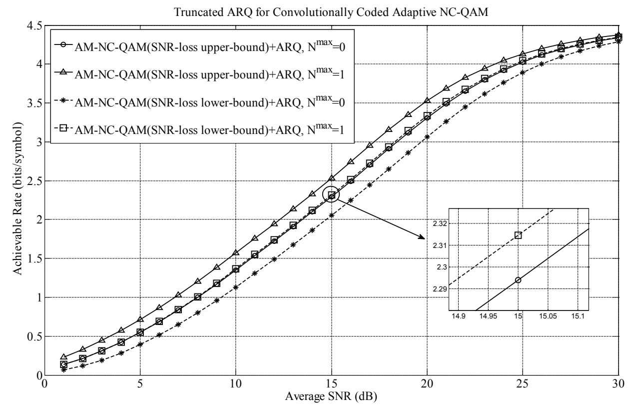

Fig. 8. Average spectral efficiency versus SNR for coded adaptive NC-QAM with truncated-ARQ (parameters are obtained similar to Table I)

has been shown to improve the system throughput of the DF-TWR downlink. Based on the SNR-loss imposed by NC-QAM, we have conceived a new transmission mechanism for the proposed scheme. Upper- and lower-bounds of the SNR-loss were used for evaluating the performance of this cross-layer design. Our numerical results showed that the proposed adaptive NC-QAM amalgamated with truncated-ARQ achieves a beneficial performance gains, both in terms of increasing the throughput of the DF-TWR downlink and in terms of reducing the packet loss rate. It is also shown that the SNR-loss remains modest.

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