Network-Coding-Aware Link Adaptation for Wireless Broadcast Transmission

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***Abstract*—We present a network-coding-aware link adaptation scheme for wireless broadcast transmission, which can achieve significantly higher throughput compared to schemes which always ensure correct decoding by the weakest link receiver. We evaluate the performance for the broadcast phase of a two-way relay channel based on average SNR feedback. If dynamic switch between the bit-wise XOR network coding scheme and the generalized multiplicative network coding is allowed, a less than 1% throughput loss compared to ideal network coding can be achieved in most SNR regions, and a less than 6% throughput loss can be guaranteed regardless of link asymmetry.**

***Index Terms*—Network Coding, Link Adaptation, Wireless Broadcast, Bidirectional Relaying.**

I. Introduction

Significant research has been recently devoted to network coding (NC) [1] based schemes in wireless broadcast transmission to reduce the total number of transmission needed, and thereby to increase the throughput. For example, in the two-way relay channel (TWRC) where two users exchange information through a relay node, [2] proposed a bitwise XOR operation of the information bits at the relay node to reduce the number of transmission slots needed from four to three. Subsequent works aimed at further decreasing the number from three to two, by allowing simultaneous transmission from the users to the relay node and performing some mapping or denoising (e.g., [3], [4]) at the relay node. Information-theoretical results [5] have shown that in the broadcast phase of TWRC, information transmission to the two users at rates equivalent to the individual link capacities can be simultaneously realized. However, practical bit-level NC-based solutions either suffer from channel asymmetry (e.g., bitwise XOR) or power loss (e.g., superposition). A symbol-level multiplicative scheme has been proposed in [6], where individual messages are first PSK modulated (not necessarily using the same modulation order) and then multiplied with one another before transmission. Although channel asymmetry can be effectively combated, the PSK modulation itself is not power/spectral efficient. A generalized multiplicative NC (GMNC) approach proposed in [7] utilizes QAM modulation instead, which can recover most of the power loss while maintaining robustness against channel asymmetry.

A common assumption in most existing work in TWRC (and NC based wireless broadcast transmission) is that link adaptation performed at the relay should always ensure correct decoding of the weaker relay-to-user link. In these NC-based schemes, although the channel coding rate might be optimized for each individual link, the modulation scheme is still determined by the weaker link due to the use of a common modulation. Such approach guarantees the weaker link to not be negatively affected by the NC operation, but would often result in significant system throughput degradation due to limiting the user with a strong link to a low order modulation. To overcome this limitation, we propose a new network-coding-aware link adaptation scheme for wireless broadcast transmission to maximize the sum throughput of individual links, where the modulation order is the only parameter to be optimized. The proposed scheme is applied to XOR and GMNC and then compared to the optimal NC solution (i.e., upper bound performance) in the broadcast phase of TWRC for different levels of channel asymmetry. When GMNC is used, the novel link adaption scheme almost achieves the upper bound of NC for the majority of the SNR combinations.

The rest of this paper is organized as follows. Section II presents the NC-aware link adaption scheme for wireless broadcast transmission and Section III analyzes its performance in the context of TWRC. Section IV presents link-level simulation results and compares it to traditional link adaption methods. Section V concludes this letter.

II. Proposed Scheme

We consider the link adaptation in wireless broadcast transmission where a network coded signal is transmitted from an intermediate relay node to K receivers. Assuming a flat fading i.i.d. Rayleigh channel on each transmitted symbol[1] from the relay to each receiver, the received signal at receiver U_i, $i = 1, 2, \ldots, K$, can be written as

$$y_i = \sqrt{P} h_i z + n_i, \tag{1}$$

where z is the complex-valued symbol from the NC operation with normalized power $E\{|z|^2\}=1$, h_i is the channel coefficient, P is the transmit power per symbol, and n_i is the complex Gaussian noise at U_i with double sided power spectral density N_0. The instantaneous SNR is therefore $\gamma_i \triangleq P|h_i|^2/N_0$, with probability density function

$$f(\gamma_i, \Gamma_i) = \frac{1}{\Gamma_i} e^{-\gamma_i/\Gamma_i},\ \gamma_i \geq 0,$$

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[1] We focus on fast fading here, but the statements are readily extended to slow fading scenarios where the channel coefficients h_i may remain unchanged during the transmission of a sequence of symbols.

where $\Gamma_i = E\{|h_i|^2\}P/N_0$ is the average SNR. Given an instantaneous SNR γ with M-QAM modulation, the corresponding symbol error rate (SER) can be approximated as [8]

$$P_S(\gamma, M) = 2\left(1 - 1/\sqrt{M}\right) \operatorname{erfc}\left(\sqrt{\frac{3\gamma}{2(M-1)}}\right). \tag{2}$$

For simplicity, it is assumed that the messages intended for user U_i have been correctly decoded by the relay node before the broadcast transmission, and user U_i has sufficient side information to retrieve its messages from the NC symbols. Given the average SNR Γ_i, the relay node takes $\log_2(M_i)$ bits, denoted as b_i, from the messages intended for U_i. These information bits $(b_1, \dots, b_K)$ are then combined together to generate the NC symbol z which will be broadcasted to all receivers. Since there are many ways to generate the NC symbol z, the SER of U_i (denoted by $P_{S,i}$) is dependent on the channel quality (via instantaneous SNR γ_i), the number of information bits contained in z (via $M_1, \dots, M_K$), and the NC scheme adopted by the relay node. Given a specific NC scheme at the relay node, the proposed NC-aware link adaptation scheme selects $(M_1^*, \dots, M_K^*)$ based on the average SNRs $(\Gamma_1, \dots, \Gamma_K)$ such that the sum throughput

$$\sum_{i=1}^{K} (1 - P_{S,i}(\Gamma_i, M_1^*, \dots, M_k^*)) \log_2(M_i) \tag{3}$$

is maximized.

The proposed NC-aware link adaptation has three main features. 1) The link adaptation is based on the users' average SNRs. The usage of average rather than instantaneous SNR feedback is meant to reduce the amount of required signaling and increase the robustness against channel variation and estimation errors. 2) The dependence of the sum throughput on the specific NC scheme has been incorporated into the SER $P_{S,i}(\Gamma_i, M_1, \dots, M_k)$. As a consequence, modification of the NC operation only requires an update of the SER without affecting the existing link adaptation structure. This feature is crucial in the sense that it increases both the NC design freedom and forward compatibility. 3) The sum throughput is calculated based on uncoded SER. Following the framework proposed in [9], channel codes optimized for AWGN channels can be applied to flat fading scenarios with the same approximate coding gains. We can therefore optimize the channel coding separately for each user to meet the specific bit/block error rate (BER/BLER) requirements per link. As a byproduct, a better trade-off between high modulation order and low error probability can be achieved without limiting the broadcast transmission to the weakest link.

As channel coding has been decoupled from the modulation selection and network coding operations, the proposed NC-aware link adaptation for wireless broadcast transmission can be easily integrated with existing link adaption schemes which are designed for point-to-point transmission. Though in general network and channel coding cannot be separated in a communication network without loss of optimality, it is shown in [10] that if the uplinks are orthogonal, the separation theorem also holds for TWRC. We will therefore not explicitly account for channel coding in this letter.

III. Performance Analysis for TWRC

For illustration we apply the proposed NC-aware link adaptation scheme in TWRC, assuming that the relay has correctly decoded each user's information in the uplink phase, and user U_i has sufficient side information to retrieve information bits b_i from z. In the broadcast phase, the relay adaptively selects (M_1^*, M_2^*) based on the average SNRs (Γ_1, Γ_2) such that the sum throughput can be maximized, i.e.,

$$(M_1^*, M_2^*) = \arg\max_{M_1, M_2} \sum_{i=1}^{2} (1 - P_{S,i}(\Gamma_i, M_1, M_2)) \log_2(M_i). \tag{4}$$

A. Optimal NC

As an upper bound, the optimal NC strategy is able to transmit at the individual links' capacities as suggested by [5], without being constrained by the other link. Given the average SNR Γ_i, the corresponding SER is therefore

$$P_{S,i}(\Gamma_i, M_1, M_2) = \int P_S(\gamma, M_i) \frac{e^{-\gamma/\Gamma_i}}{\Gamma_i} d\gamma. \tag{5}$$

B. XOR-based NC

When XOR-based NC (or any other pre-modulation NC) is used, a common modulation is selected for the broadcast transmission owing to the fact that the NC operation occurs before the modulation operation. In general, a low modulation order is chosen to ensure correct reception at the weakest node (e.g., [11]), which often causes throughput degradation for stronger nodes. One way to overcome this limitation, as proposed in [12], is to use a high order modulation suitable to the stronger node and meanwhile add extra channel coding[2] for the weaker node before the XOR operation to ensure correct reception. Alternatively, when NC-aware link adaptation is used, the modulation order is selected to maximize the sum throughput as in (4) but with the additional constraint $M_1 = M_2$. The corresponding SER is therefore

$$P_{S,i}(\Gamma_i, M_1 = M_2 = M) = \int P_S(\gamma, M) \frac{e^{-\gamma/\Gamma_i}}{\Gamma_i} d\gamma. \tag{6}$$

C. GMNC

GMNC [7] is a post-modulation approach to NC where the NC operation consists of a complex-domain multiplication of modulated symbols $s_1(b_1)$ and $s_2(b_2)$ (i.e., $z = s_1 \times s_2$) at the relay and a division by a-priori information at the user side in order to retrieve the desired information. Unlike bit-level NC schemes, GMNC has the virtue of allowing different modulations to be utilized for individual links. With GMNC, the SERs are given by ($i, j \in \{1, 2\}$ and $i \neq j$)

$$P_{S,i}(\Gamma_i, M_1, M_2) = \frac{1}{M_j} \sum_{k=1}^{M_j} \int P_S(\gamma \cdot A_k(M_j), M_i) \frac{e^{-\gamma/\Gamma_i}}{\Gamma_i} d\gamma. \tag{7}$$

[2]The extra channel coding, which performs one-to-one mapping from short bit-vectors to long bit-vectors, essentially selects a subset of the high order modulation constellations for message transmission.

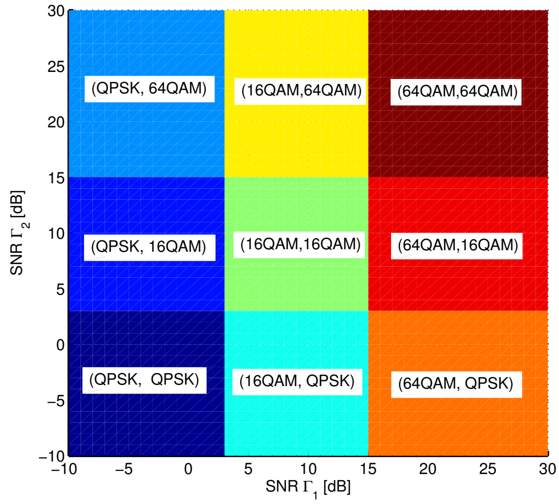

Fig. 1. The *optimal* modulation of (user 1, user 2) for the optimal NC.

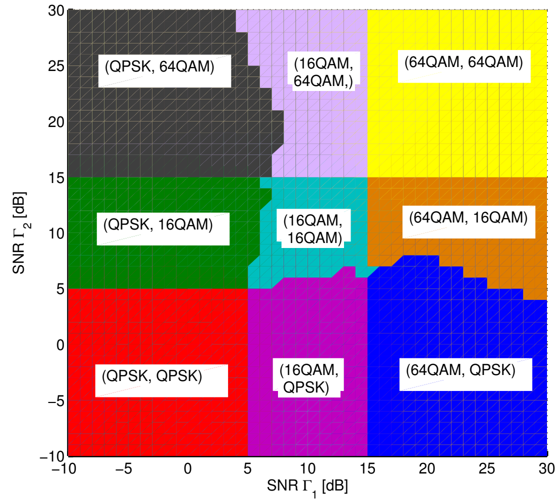

Fig. 3. The *optimal* modulation choice for GMNC based on link SNRs.

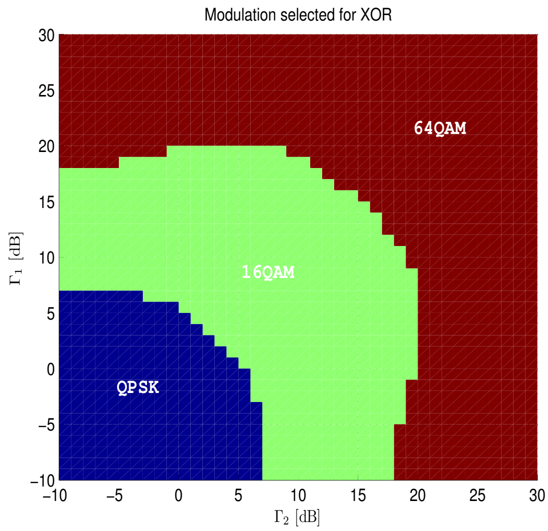

Fig. 2. The *optimal* modulation for XOR-based NC.

$A_k(M)$ in (7) is the power of the M-QAM modulated symbol when the kth constellation point is used [7]. The effective SNR $\gamma{\cdot}A_k(M)$ is due to the multiplication of modulated symbols, which may cause noise amplification by some constellation points when M is large. Such degradation can be alleviated by proper constellation rearrangement [7]. We will however focus on classical M-QAM modulation to highlight the benefit of the proposed NC-aware link adaptation scheme.

D. Extension to TWRC with $K > 2$ Users

There are many ways to extend the current work to support $K > 2$ users. For example, the NC symbol for XOR can be generated by $z = s(b_1 \oplus \cdots \oplus b_K)$ after introducing appropriate channel codes, and $z = s_1(b_1) \times \cdots \times s_K(b_K)$ for GMNC. However, such straightforward extension might incur performance degradation compared to the optimal NC for the following two reasons: the optimality of network-channel coding separation may not hold for $K > 2$; throughput loss will increase with K for both XOR (due to increased link asymmetry) and GMNC (due to worse noise amplification). On the other hand, there are more degrees of freedom can be exploited in NC design when more users are involved. For instance, users can be paired based on their channel qualities to maximize the sum throughput. We leave this for future work.

IV. Simulation Results and Discussions

We evaluate the performance of our proposed NC-aware link adaptation scheme in a TWRC setup with flat i.i.d. Rayleigh fading channels. The average SNR for all relay-to-user links are known by the relay node. No channel codes are used and the following modulations are used in solving (4): QPSK, 16QAM and 64QAM (i.e., M = 2, 4, 6). The SERs in (5), (6), and (7) are calculated by link-level simulation based on 10^9 channel realizations per SNR value.

The main difference between Optimal NC, XOR-based NC and GMNC is how the modulation order is selected given a certain SNR pair (Γ_1, Γ_2). The adaptive modulation for all three schemes is based on solving (4), which is an optimization problem that can be easily solved by exhaustive search due to the few combinations of (M_1,M_2) that are to be optimized with. The SER of the three different schemes is, however, different. For instance, that of *Optimal NC* is based on (5), *XOR-based NC* is based on (6) and *GMNC* is based on (7). *Optimal NC* allows to optimize each link independent of the other link's SNR, and the consequent modulation selection is shown in Fig. 1 where it can be readily seen that the modulation of each user is independent of the other user's link quality (i.e. the modulation of user U_i is affected by Γ_i only).

As for *XOR-based NC*, a common modulation has to be selected since the NC operation takes place prior to modulation. This behavior is observed in Fig. 2. This is the main

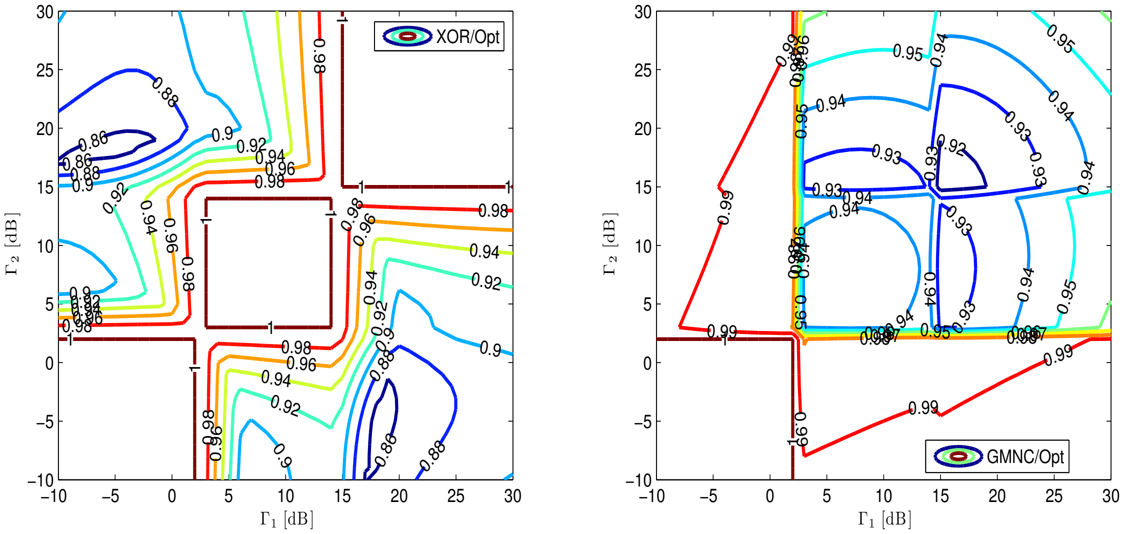

Fig. 4. Broadcast phase sum throughput of NC-aware link adaptation with XOR (left) and GMNC (right), normalized by the sum throughput of optimal NC.

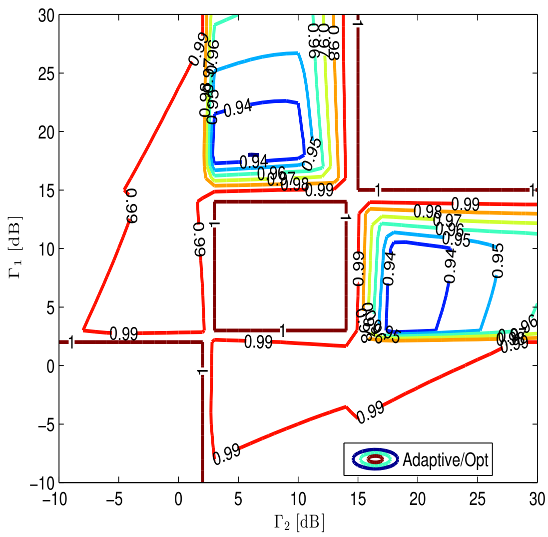

Fig. 5. Sum throughput of adaptive NC compared to optimal NC.

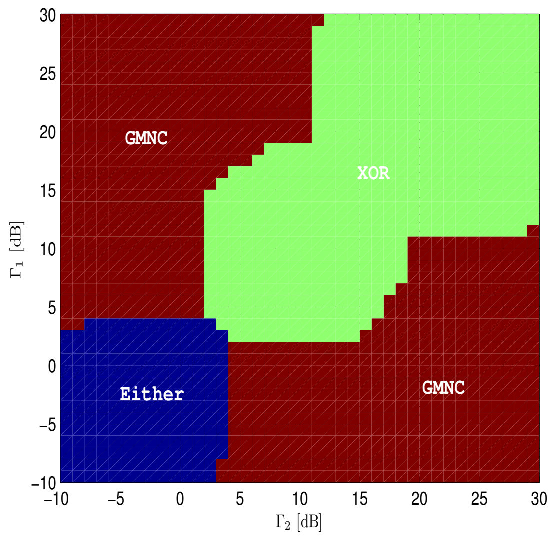

Fig. 6. Average SNR thresholds for adaptive NC scheme selection.

reason for performance degradation at asymmetric SNR where it is beneficial to have the possibility to choose different modulations for different links.

On the other hand, *GMNC* allows the different links to use different modulations as seen in Fig. 3. The modulation selection is not exactly the same as for Optimal NC due to the fact that the link quality of one user influences the performance of the other user through the network decoding (i.e. division with a-priori information) operation. However, this influence is rather minimal as it will be observed from subsequent results. It should be noted that in a practical system, the optimal modulation selection can be performed/trained offline and the relay would simply choose the optimal modulations based on the reported SNR.

Fig. 4 shows the sum throughput of NC-aware link adaptation with XOR and GMNC, normalized by the sum throughput of the optimal NC. It can be seen that both schemes have a comparable performance to the optimal NC scheme: GMNC provides at worst an 8% loss on sum throughput compared to optimal NC whereas the equivalent number is 14% for XOR. XOR has an optimal performance when both users have equal or slightly different SNR, while GMNC performs better in cases of high link asymmetry. Although the results here are based on average SNR feedback, it has been verified through simulations that using instantaneous, instead of average, SNR feedback does not influence the relative performance of the different schemes. This demonstrates the robustness of proposed scheme against channel variations.

With both schemes having complementary characteristics, an adaptive variant that switches dynamically between them

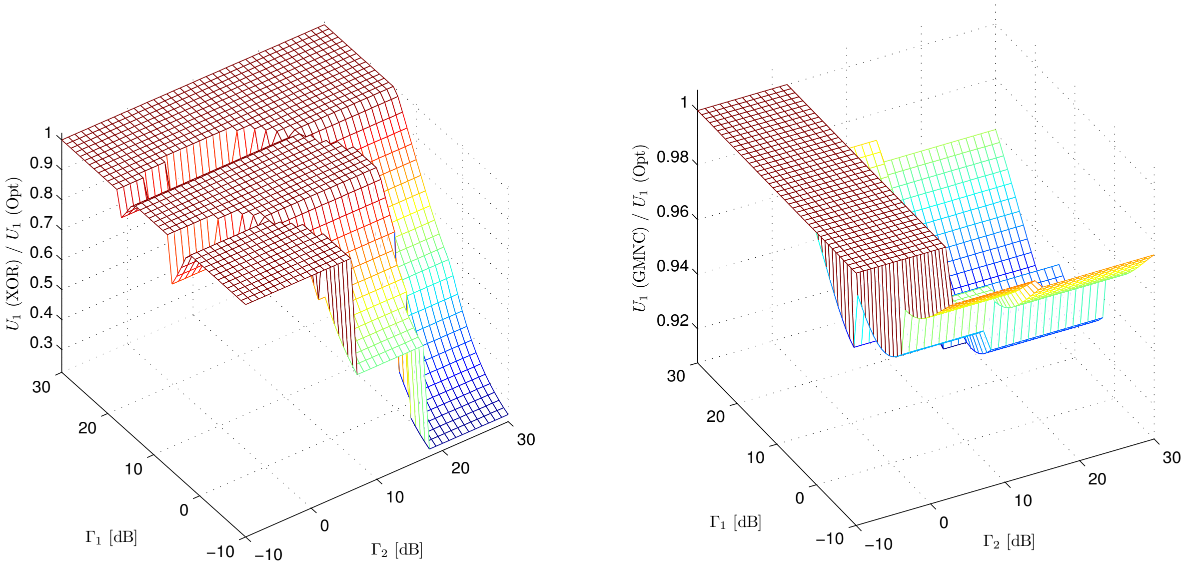

Fig. 7. Fairness of NC-aware link adaptation with XOR (left) and GMNC (right) in terms of user throughput, normalized by that of optimal NC.

is of high interest to optimize the sum throughput. As the dynamic selection of NC schemes is performed based on average SNR feedback, a high signaling load can be avoided while achieving increased robustness against channel estimation noise. Fig. 5 shows the relative sum throughput of adaptive NC compared to the optimal NC, where the loss in sum throughput is less than 1% in most channel setups, and is at most 6% regardless of link asymmetry. Fig. 6 shows the SNR thresholds for selecting the most suitable NC scheme, which can be performed *offline* to further reduce complexity.

In order to observe how the user performance is affected by XOR and GMNC when NC-aware link adaptation is used, Fig. 7 shows the relative throughput (normalized by that of the optimal NC) of U_1 as a function of Γ_1 and Γ_2. Noting the different scale on the z-axis, it can be observed that XOR significantly limits the weak user when the other link is very strong. That is because the sum throughput is optimized by choosing a high modulation order suitable to the strong link, resulting in a very high SER and consequently low throughput for the user with weaker link. On the other hand, GMNC leads to minor throughput degradation (less than 8%) due to noise amplification. Compared with XOR, GMNC has better end-uesr experience and improved fairness as users are not considerably limited by their NC pair.

V. Conclusions

We present a network-coding-aware link adaptation scheme for wireless broadcast transmission and apply it to XOR-based network coding and GMNC. One main advantage of GMNC is that it results in minor throughput limitation of the users by their NC pairs. As XOR and GMNC have complementary characteristics, an adaptive scheme that switches between them was devised based on average SNR feedback. In the broadcast phase of a two-way relay channel, simulation results have shown that less than 1% throughput loss compared to ideal network coding can be achieved in most channel setups, and less than 6% throughput loss can be guaranteed regardless of link asymmetry. When GMNC is combined with NC-aware link adaptation, better user fairness can be achieved. Furthermore, the possibility to decouple network coding, channel coding, and modulation selection gives more flexibility and lower complexity in system design.

Acknowledgments

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