Maximum Throughput Adaptive Rate Transmission Scheme for Multihop Diversity Aided Multihop Links

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***Abstract*—In multihop diversity aided multihop links, the number of bits transmitted in each Time Slot (TS) is affected by both the Channel Quality (CQ) and the Buffer Fullness (BF), when adaptive modulation is employed. We assume that every node has buffers for temporarily storing its received packets for further transmission at instances of good CQ. For the sake of improving the throughput, a Maximum Throughput Adaptive Rate Transmission (MTART) scheme was proposed, where the specific hop having the capability of transmitting the highest number of bits (packets) will be activated. If more than one hops are capable of transmitting the same number of bits, the particular hop having the highest CQ (reliability) is activated. We demonstrate that the MTART scheme has 8 dB gain at the Outage Probability (OP) of 10^{-3} and has 3 dB gain in terms of the throughput attained in comparison to the conventional adaptive modulation aided scheme.**

***Index Terms*—Multihop communication, adaptive modulation, relay, BER, outage probability, buffer.**

I. Introduction

In the context of multi-hop links (MHLs), it has typically been assumed that the information is successively transmitted from the Source Node (SN) to the Destination Node (DN) on a node-by-node basis, without any store-and-wait stage at the intermediate Relay Nodes (RNs) [1–3]. We refer to this scheme as the Conventional Multi-Hop Link (CMHL) in our forthcoming discourse for convenience. The information is transmitted over a single hop during its scheduled Time-Slot (TS), regardless of its link quality which is quantified, for example, by its Signal-to-Noise Ratio (SNR). Hence, the overall reliability of a CMHL is dominated by that of the poorest hop and a route outage occurs, once an outage is encountered in any of the constituent hops.As a remedy, the seminal concept of MultiHop Diversity (MHD) was proposed in [4–7], where all the nodes of a MHL are assumed to have a buffer for temporarily storing their received packets, so that they may be ‘transmitted at instances of good Channel Quality (CQ). During each TS, the specific hop having the best CQ, for example, the highest SNR is activated for transmitting the pre-stored packets.

Moreover, Adaptive Modulation and Coding (AMC) [8] is a term routinely used in wireless communications for indicating that system parameters are near-instantaneously adapted to the CQ, which will enhance the system's performance. The authors of [9] characterized adaptive modulation relying on Space-Time Block Code (**STBC**) aided transmission using Maximum Ratio Combining **MRC** for single-hop transmissions over Nakagami-m channel. Maximum throughput optimization was studied in [10] by finding the AMC mode-switching thresholds of different modulation schemes. Yang *et al* [11] combined adaptive modulation with Generalized Selective Combining (GSC) under the terminology of *joint adaptive modulation and diversity combining*. This work was then carried on in [12, 13]. Aniba and Aissa [9] discussed adaptive modulation in conjunction with packet combining and truncated ARQ for transmission over MIMO Nakagami fading channels.

Against this background, we combine the advantages of MHD and adaptive modulation for improving the achievable performance. *The new contributions of this paper are*
1. A Maximum Throughput Adaptive Rate Transmission (MTART) regime was proposed;
2. The outage probability and the throughput are analyzed.

The rest of this paper is organized as follows. Section II presents our system model. Then Section III and Section IV analyze the achievable performance for transmission in both general and specific Nakagami-m-fading channel scenarios. In Section V, our numerical and simulation results are compared, while our conclusions are offered in Section VI.

The financial support of the RC-UK under the auspices of the India-UK Advanced Technology Centre, the support of European Research Council's Advanced Fellow Grant, the support of the EU's Concerto project and the UK/China scholarships for excellence programme is gratefully acknowledged.

II. System Model

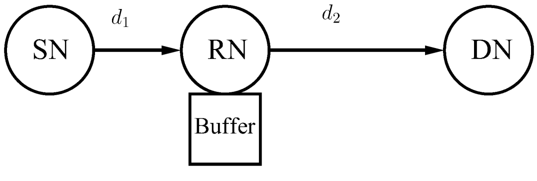

Fig. 1. System model for a two-hop wireless link, where the SN S sends messages to the DN D via an intermediate RN R.

The MHL considered in this contribution is the same as the one studied in [14, 15], which is shown in Fig. 1. The MHL consists of three nodes, namely a SN S (node 0), a RN R (node 1) and a DN D (node 2). The distance of the two hops is given by d_1 and d_2. S sends messages to D via

R. At R, the classic Decode-and-Forward (DF) protocol [16] is employed for relaying the signals. We denote the symbol transmitted by node 0 as x_0 and its estimate at D of node 2 by $x_2 = \hat{x}_0$, while the symbol estimated at R by x_1. At the packet level, they are correspondingly represented by $\boldsymbol{x}_0$, $\boldsymbol{x}_1$ and $\boldsymbol{x}_2 = \hat{\boldsymbol{x}}_0$. We assume that the signals are transmitted on the basis of TSs having a duration of T seconds. In addition to the propagation pathloss, the channels of the two hops are assumed to experience independent block-based flat fading, where the complex-valued fading envelope of a hop remains constant within a TS, but is independently faded for different TSs. The pathloss is assumed to obey the negative-exponential law of $d_i^{-\alpha}$, where α is the pathloss exponent, having a value between 2 and 6. We assume that the total energy per symbol transmitted from S to D is $E_s = 1$ unit, regardless of the number of hops per MHL. This one unit of energy is shared among the two transmit nodes. We assume that appropriate Energy Allocation (EA) is used for ensuring that all the receivers have the same average SNR. In this case, the ith hop's transmit energy is $E_i = \frac{d_i^\alpha E_s}{\sum_{l=1}^{2} d_l^\alpha}$. Hence, all the two hops have the same received energy of $E' = \frac{E_s}{\sum_{l=1}^{2} d_l^\alpha}$. When the $(l-1)$st node transmits a packet $\boldsymbol{x}_{l-1}$, the observations received by node l may be expressed as

$$\boldsymbol{y}_l = \sqrt{E'} h_l \boldsymbol{x}_{l-1} + \boldsymbol{n}_l, \ l = 1, 2, \tag{1}$$

where h_l represents the fading channel gain of the lth hop between node $(l-1)$ and node l, while $\boldsymbol{n}_l$ is the Gaussian noise added at node l. The fading channel gain h_l is assumed to be complex Gaussian with a zero mean and a variance of $E[|h_l|^2] = 1$. The noise samples in $\boldsymbol{n}_l$, $l = 1, 2$ obey the complex Gaussian distribution with zero mean and a common variance of $\sigma^2 = 1/2$ per dimension. Based on the above definitions and on (1), the instantaneous SNR of the lth hop is then given by $\gamma_l = E'|h_l|^2$.

In this paper, we investigate the OP and the throughput of MHLs employing our MHD scheme [14, 15] associated with adaptive M-ary Quadrature Amplitude Modulation (MQAM) [8, 10]. The assumptions are stipulated as follows:

- S always has packets for transmission in its buffer, when considering its steady state operation;
- Both S and D can store an infinite number of packets. By contrast, R can only store at most B packets;
- The fading processes of the two hops of a MHL are independent. The fading of a given hop remains constant within a packet's duration, but it is independently faded from one packet to another;
- According to the CQ, such as the SNR of a hop, the most appropriate MQAM scheme is chosen from the available set of MQAM modes for the sake of guaranteeing the required Quality-of Service (QoS), such as a specific BER;

III. Adaptive Rate Transmission over Multihop Links: General Cases

In this section, the principles of our MTART regime are first introduced. Then, in Section IV, the performance of the MHLs employing MTART is investigated, when communicating over i.i.d Nakagami-m channels.

A. Maximum Reliability Adaptive Rate Transmission: Two-Hop Case

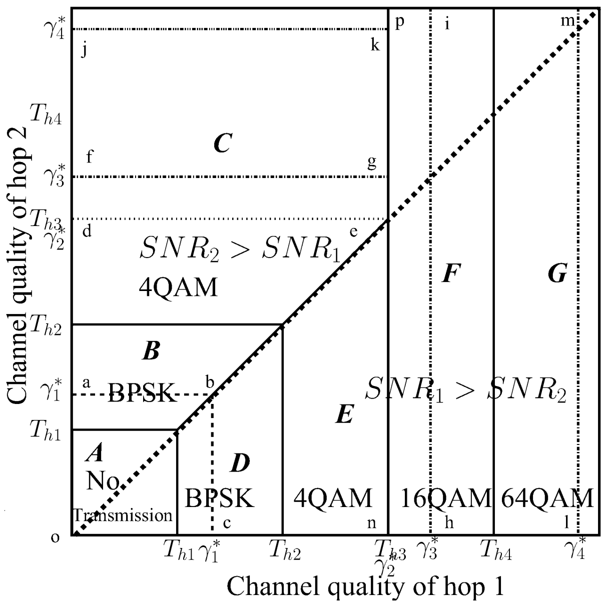

Fig. 2. Schematic diagram for explaining the maximum throughput adaptive rate transmission scheme for a two-hop link, when assuming that the RN holds two bits (packets), while the SN has an infinite number of bits (packets).

Let us start from the selection criterion of the MTART scheme. The criterion used for activating a specific hop to transmit during a TS is that of transmitting the highest number of bits (packets). When there are more than one hops offering to transmit the same number of bits, the particular hop having the highest CQ is activated. Hence, our MTART scheme achieves the highest throughput, while maintaining the target BER. Below we use a simple two-hop example associated with Fig. 2 for further augmenting the principles of the MTART.

Let us assume that the MRART scheme supports five possible data rates, associated with, 0, 1, 2, 4, and 6 bits per symbol (BPS) (packets per TS), corresponding to using 'no transmission', BPSK, QPSK, 16QAM and 64QAM. In this case, the CQ of a hop is classified into one of the five regions with the aid of four thresholds, $T_{h1} < T_{h2} < T_{h3} < T_{h4}$, as shown in Fig. 2. For the example considered, we assume that the RN currently has only two bits (packets) stored in its buffer. Hence, the highest rate of the second hop is two BPS or (packets per TS), regardless of the CQ of the second hop is. By contrast, on the first hop, any one of the five rates can be transmitted, which is dependent on the near-instantaneous CQ of the first hop. Consequently, as shown in Fig. 2, the space according to the CQ (SNR values) of the first and second hops can be divided into seven regions by the solid lines, which are the regions A, B, C, D, E, F and G. Observe in Fig. 2 that the dashed diagonal line divides the CQ space into two regions. In the region above the dashed line, the CQ of the first hop is worse than that of the second hop, while in the region below the dashed line, the CQ of the first hop is better than that of the second hop. Finally, the CQs of both hops are the same along the dashed diagonal line.

As shown in Fig. 2, when the CQs of the first and second hops fall within the region A, no data transmission is activated over either of the hops, since the channels of both hops are too poor for maintaining the required BER. Within region B, the second hop is better than the first hop and 1 BPS (packet per TS) may be transmitted reliably. In region D, the first hop's CQ is better than that of the second hop and it can support the transmission of 1 BPS (packet per TS). As shown in Fig. 2, when the CQs fall in the region C, 2 BPS (packets per TS) are transmitted by the second hop, regardless of how good the CQ is, because the RN has only two bits (packets) stored in its buffer. When the CQs fall in the region E, 2 BPS (packets per TS) are transmitted by the first hop. Finally, when the CQs are within the region F or G, the first hop is always activated for transmission, even when the second hop is more reliable than the first hop, because the first hop can now transmit 4 or 6 BPS (packets per TS). Let us now derive the PDF and CDF of the SNR for the selected hop.

B. PDF of the SNR for the Hop Selected Based on MTART: Two-Hop Links

Let us assume that the instantaneous SNR of the first hop is γ_1 and that of the second hop is γ_2. The PDFs $f(\gamma)$ of γ_1 and γ_2 are the same. Let the PDF of the SNR for the hop selected from the two hops be expressed as $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$, where $\widehat{r_i}$ is the PR of the ith hop, $i=1,2$. Here, the PR of a hop from node i to node $(i+1)$ is determined by the minimum number of packets associated with the following situations. a) The number of packets stored in the buffer of node i. b) The number of available storage packets in the buffer of node $(i+1)$. c) The maximum transmission rate expressed in packets per TS that is derived based on the CQ between node i and node $(i+1)$. Moreover, let $|\bullet|$ represent the number of logical '1' value in $|\bullet|$. For example, $|1>0|$=1, $|0>1|$=0, $\underbrace{|1>0, 2>0|}_{\text{two logic ture}}$=2, $\underbrace{|\{1,2\}>0|}_{\text{two logic ture}}$=2. Furthermore, for convenience of description, a number of terminologies are used for describing the relationship between the SNR γ_i, rate r_i and the thresholds, T_{hi}. First, the lower boundary of the PR region of the ith hop is expressed as $T_{h\widehat{r_i}}$. For example, the PR of the second hop in Fig. 2 is $\widehat{r_2}$=2 BPS (packets per TS), which is achieved in region C. Hence, the lower boundary of the second hop is $T_{h\widehat{r_2}}$=T_{h2}. Similarly, the PR of the first hop in Fig. 2 is $\widehat{r_2}$=6 BPS (packets per TS), which is achieved in region G. Correspondingly, the lower boundary of the first hop is $T_{h\widehat{r_1}}$=T_{h4}. Secondly, in our description, a symbol $\oplus$ used in the subscript represents a specifically defined operation "plus in subscript" as exemplified by $T_{h3\oplus 1}=T_{h4}$, $T_{h\widehat{r_2}\oplus 1}=(T_{h\widehat{r_2}})_{\oplus 1}=T_{h2\oplus 1}=T_{h3}$. Furthermore, when the CQ of the lth hop is γ_i, the region constrained by the two thresholds and the corresponding rate, which expressed as $T^l_{h\gamma_i}$, $T^l_{h\gamma_i\oplus 1}$ and $r^l_{\gamma_i}$, respectively becomes known. For example, as shown in Fig. 2, γ_3^* of the first hop is between T_{h3} and T_{h4}. Hence, we have $T^1_{h\gamma_3^*}=T_{h3}$ and $T^1_{h\gamma_3^*\oplus 1}=T_{h4}$, and correspondingly, $r^1_{\gamma_3^*}=4$, since 16QAM is transmitted, when γ_1 is in this region.

Having defined the above terminologies, let us now derive the PDF $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$ of the SNR step by step. Firstly, $p_{\widehat{r_1},\widehat{r_2}}(0)$ is the probability that none of the two hops is activated, since we have $\gamma_1<T_{h1}$ and $\gamma_2<T_{h1}$, hence an outage occurs. This probability corresponds to region A in Fig. 2, which can be expressed as

$$p_{\widehat{r_1},\widehat{r_2}}(0)=\left[\int_0^{T_{h1}} f(\gamma_1)d\gamma_1\right]^{|\widehat{r_1}>0|}\left[\int_0^{T_{h1}} f(\gamma_2)d\gamma_2\right]^{|\widehat{r_2}>0|}. \tag{2}$$

Owing to the assumption that both channels obey the same distribution $f(\gamma)$, we have

$$p_{\widehat{r_1},\widehat{r_2}}(0)=\left[\int_0^{T_{h1}} f(\gamma)d\gamma\right]^{|\{\widehat{r_1},\widehat{r_2}\}>0|}, \tag{3}$$

where, according to our pervious definitions, we have $|\{\widehat{r_1},\widehat{r_1}\}|$=2.

According to our MTART regime, once a hop has been selected, the minimum channel SNR of the selected hop is T_{h1}. Hence, the selected hop's SNR is either larger than T_{h1} or 0. Consequently, we have

$$p_{\widehat{r_1},\widehat{r_2}}(\gamma)=0, \text{ when } \gamma\in(0,T_{h1}). \tag{4}$$

As shown in Fig. 2, if the selected hop's SNR falls between (T_{h1},T_{h3}), such as γ_1^* of Fig. 2, then the specific hop having the higher SNR is selected. Hence, $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$ can be expressed as

$$p_{\widehat{r_1},\widehat{r_2}}(\gamma)=\underbrace{f(\gamma)\int_0^{\gamma} f(\gamma_1)d\gamma_1}_{\text{second hop selected}}+\underbrace{f(\gamma)\int_0^{\gamma} f(\gamma_2)d\gamma_2}_{\text{first hop selected}},$$
$$\text{when } \gamma\in[T_{h1},T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1}), \tag{5}$$

where $T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1}$=$T_{h3}$ is the upper boundary of the region. Note that here we have $\min(\widehat{r_1},\widehat{r_2})=2$. Hence, $T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1}=3$.

Finally, when the channel SNR of the selected hop is higher than T_{h3}, $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$ may be characterized as follows. As shown in Fig. 2, if the first hop having an SNR of γ_3^* is selected, the second hop's SNR can be any arbitrary value, since the second hop can only transmit a maximum of 2 BPS, while the first hop transmits 4 BPS at γ_3^*. By contrast, if the second hop having an SNR of γ_3^* is selected, the first hop's SNR is at most T_{h3}. Otherwise, the first hop would be selected. Consequently, for $\gamma>T_{h3}$, $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$ can be formulated as

$$\begin{aligned}p_{\widehat{r_1},\widehat{r_2}}(\gamma)=&\underbrace{f(\gamma)\int_0^{\infty} f(\gamma_2)d\gamma_2}_{\text{first hop selected}}+\underbrace{f(\gamma)\int_0^{T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1}} f(\gamma_1)d\gamma_1}_{\text{second hop selected}}\\ =&f(\gamma)\left[1+\int_0^{T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1}} f(\gamma_1)d\gamma_1\right],\\ &\text{when } \gamma\in(T_{h\min(\widehat{r_1},\widehat{r_2})\oplus 1},\infty).\end{aligned} \tag{6}$$

Fig. 3 shows the PDF $p_{\widehat{r_1},\widehat{r_2}}(\gamma)$ of a two-hop link, where each hop experiences flat Rayleigh fading having an SNR obeying the PDF of $f(\gamma)=\frac{1}{\bar{\gamma}}e^{-\frac{\gamma}{\bar{\gamma}}}$ asociated with $\bar{\gamma}=1$. The curves were evaluated from (2), (4), (5) and (6), respectively. In our evaluations, we assumed that the average received SNR of each hop was 10dB. Correspondingly, the MQAM switching thresholds were set to $[0.17\ 0.35\ 1.53\ 5.6]$. In the figure, four sets of PRs were considered, which were [6 0], [6 1], [6 2] and [6 6] BPS. As shown in Fig. 3, when $\widehat{r_1}, \widehat{r_2} = [6\ 0]$ is considered, only the first hop may be activated. Hence, the PDF of the SNR is the same as that of a single Rayleigh fading channel, when $\gamma \in (T_{h1}, \infty)$. The OP evaluated from (2) is 16% in this scenario, which is represented by a triangle marker at SNR= 0. For all the other cases, the outage probability is 2.6%, which is also shown in the figure by the overlapping circle, star and square markers at channel $SNR = 0$. In the case of $\widehat{r_1}, \widehat{r_2} = [6\ 2]$ BPS, we observe a sharp PDF peak at SNR=1.5, which occurs at T_{h3}. We infer from Fig. 3 that the average CQ of the selected hop associated with $\widehat{r_1}, \widehat{r_2} = [6\ 1]$ BPS and $\widehat{r_1}, \widehat{r_2} = [6\ 2]$ BPS is better than that of $\widehat{r_1}, \widehat{r_2} = [6\ 0]$ BPS, but worse than that of $\widehat{r_1}, \widehat{r_2} = [6\ 6]$ BPS.

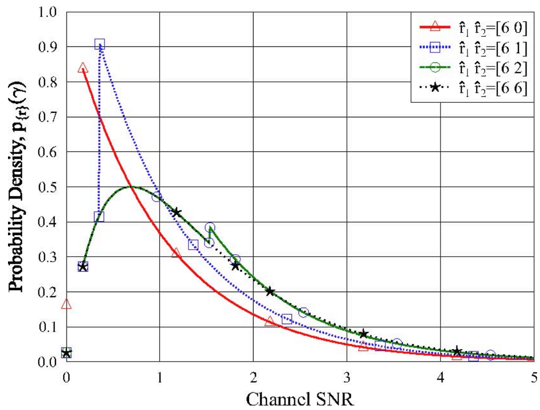

Fig. 3. The SNR PDF of 2-hop links, where each hop obeys flat Rayleigh fading associated with the channel SNR's PDF of $f(\gamma) = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}$ and $\bar{\gamma} = 1$. The thresholds $T_{hi}, i = 1, 2, 3, 4$ were set to $[0.17\ 0.35\ 1.53\ 5.6]$, which were configured for maintaining BER<0.03 as used in [10]. The SNR-PDFs were evaluated from (2), (4), (5) and (6).

IV. Adaptive Rate Transmission over Multihop Links Experiencing i.i.d Nakagami-m Fading

In Section III we have discussed the general case of using our MTART regime over MHLs. In this section, the general results are applied to the specific scenario of a i.i.d Nakagami-m fading channel. Specifically, the expressions of the OP, achievable throughput as well as bandwidth-efficiency are analyzed.

A. State Transition Matrix

The concept of State in buffer-aided systems was proposed in [5, 6]. upon assuming that the buffer size of the RN is B packets, the state is defined as $S_b = b$ when b packets are stored in the RN. Therefore, the total number of states is $(B+1)$. Given $(B+1)$ states, a state transition matrix denoted by $\boldsymbol{T}$ can be populated by the state transition probabilities $\{\boldsymbol{T}_{i,j} = P(s(t+1) = S_j | s(t) = S_i),\ i, j = 0, 1, \ldots, B\}$. Let us now find $\boldsymbol{T}$.

The element $\boldsymbol{T}_{i,j}$ in $\boldsymbol{T}$ denotes the state transition probability from state i to state j after a single TS. If state j cannot be reached from state i in a single TS, $\boldsymbol{T}_{i,j}$ is zero. Specifically, $\boldsymbol{T}_{i,i}$ means that no packets are transmitted by the system, hence an outage occurs. Therefore, $\boldsymbol{T}_{i,i}$ represents the OP. When state i is changed to state j, a unique hop should be correspondingly activated and the number of packets to be transmitted is also known. Let us assume that the lth hop should be activated and that $r_{i\to j}$ packets should be transmitted, when the system evolves from state i to j. In this case, the state-transition probability $\boldsymbol{T}_{i,j}$ can be evaluated as

$$\boldsymbol{T}_{i,j} = \int_{T_{hr_{i\to j}}}^{T_{hr_{i\to j}\oplus 1}} p^{l}_{\widehat{r_1},\widehat{r_2}}(\gamma) d\gamma, \tag{7}$$

where $p^{l}_{\widehat{r_1},\widehat{r_2}}(\gamma)$ is given by part of (5) and (6). Explicitly for $l = 1$ the "first hop is selected", while for $l = 2$ the "second hop is selected".

Having obtained the state transition matrix $\boldsymbol{T}$, the steady-state probabilities can be computed according to [17] as

$$\boldsymbol{\pi} = \boldsymbol{T}^T \boldsymbol{\pi}, \tag{8}$$

where we have $\boldsymbol{\pi} = [\pi_0, \pi_1, \ldots, \pi_B]^T$ and π_i is the steady-state probability that the 2-hop link is in state S_i [18]. The steady-state probability of a state is applied as the expected value of the probability of this specific state in system. The knowledge of the steady-state probability of every state allows us to determine the Probability Mass Function (PMF) of a buffer.

B. Achievable Throughput

Given the state transition matrix $\boldsymbol{T}$ and the steady-state probabilities $\boldsymbol{\pi}$, the throughput Φ_T of a MHL can be evaluated. Given that the probability of the system evolving from state i to state j is $\pi_{i-1}\boldsymbol{T}_{i,j}$ and that $r_{i\to j}$ packets are transmitted over a hop, the achievable throughput may be expressed by considering all possible state transitions, yielding

$$\Phi_T = \sum_{i=1}^{(B+1)} \sum_{j=1}^{(B+1)} \pi_{i-1} \boldsymbol{T}_{i,j} r_{i\to j}. \tag{9}$$

C. Outage Probability and Its Bound

Similarly to Subsection IV-B, given the state transition matrix $\boldsymbol{T}$ and the steady-state probabilities $\boldsymbol{\pi}$, the OP of an 2-hop MHL may be readily expressed as

$$P_O = \sum_{i=1}^{(B+1)} \pi_{i-1} \boldsymbol{T}_{i,i}. \tag{10}$$

Note that the lower-bound of the OP is given by (2) associated with the setting of $|\widehat{r} > 0| = 2$.

D. Bandwidth-Efficiency

The single-hop bandwidth-efficiency with a given $\{\widehat{r_1}, \widehat{r_2}\}$ of the selected hop is

$$C_{\{\widehat{r_1},\widehat{r_2}\}} = \int_0^\infty \log_2(1+\gamma) p_{\{\widehat{r_1},\widehat{r_2}\}}(\gamma) d\gamma. \tag{11}$$

When communicating over Nakagami-m fading channels. Upon substituting (2), (4), (5) and (6) into (11), and carrying out some futher manipulations, we arrive at (13), where b_k^j was given in [19](16), and $NC(a,p,q,T_1,T_2)$ is defined as $NC(a,p,q,T_1,T_2) = \int_{T_1}^{T_2} \ln(1+a\gamma)\gamma^p \exp(-\frac{q\gamma}{\bar{\gamma}})d\gamma$, where a,p and q are integers. The close-form expression of this integral can be found in [20].

Given $C_{\{\widehat{r_1},\widehat{r_2}\}}$ of (13), the exact end-to-end bandwidth-efficiency C of a MHL may be calculated by considering all the possible states, yielding

$$C = \frac{1}{2}\sum_{i=1}^{(B+1)} \pi_{i-1} C_{\{\widehat{r_1},\widehat{r_2}\}_{S_i}}, \tag{12}$$

where the factor $\frac{1}{2}$ is due to having 2 TSs owing to the orthogonal time division operation assumed in [21].

V. Performance Results

In this section, the OP and the attainable throughput of the MHLs are investigated in order to illustrate the effect of the RN's buffer size B.

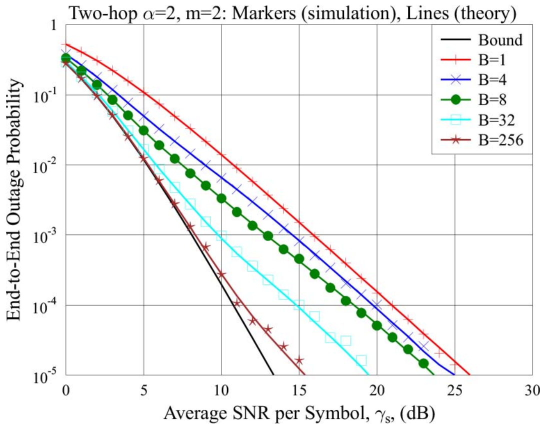

Fig. 4. The OP performance using our MTART in a two-hop link over Nakagami-m channel when $m = 2$. The MQAM switching - thresholds were configured for BER=0.03 according to [10]. The related formula used for computing the results is (10).

Fig. 4 characterizes the OP of two-hop links communicating over Nakagami-m fading channels. Note that in our numerical computations and simulations, the outage threshold (T_{h1}) of each hop was adjusted for maintaining a BER of 0.03 for a single-hop link. The theoretical results were obtained by evaluating (10). The OP of conventional adaptive modulation is also provided for the sake of comparison in this figure, which corresponds to $B = 1$, i.e. to the absence of buffer. A significant improvement is observed for the RN employing buffers of a sufficiently high size. For example, the SNR gain at OP=10^{-3} is 8dB, because in conventional adaptive modulation an outage occurs, when the CQ of a *single* hop is lower than the outage threshold. By contrast, in our proposed MTART regime an outage occurs only when the CQs of *all* hops are lower than the outage threshold of the RN employing buffers.

Fig. 5 shows the throughput/bandwidth-efficiency of two-hop links communicating over Rayleigh channels. The theoretical throughput results were evaluated using (9), while the bandwidth-efficiency results were obtained from (13) and (12).

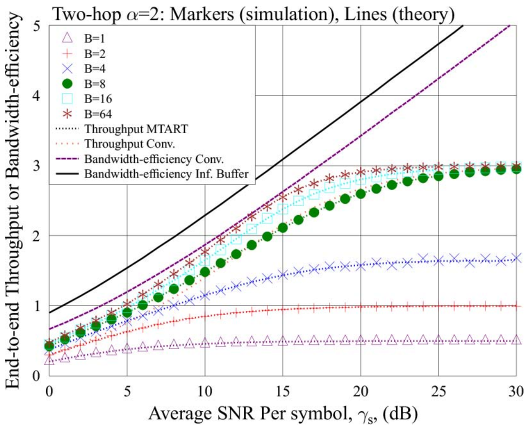

Fig. 5. The throughput and capacity for two-hop link over Rayleigh channel.

Furthermore, the curves with markers represent the end-to-end throughput for a specific buffer size. The solid line at the top represents the bandwidth-efficiency, when the RN employs an infinite buffer size. By contrast, the second line from the top, which is a dashed-curve, represents the bandwidth-efficiency of the conventional adaptive scheme. The dotted line, which is roughly overlapping with the buffer scenario of $B = 8$ line represents the throughput $\Phi_{Conv.}$ for the conventional two-hop link, which was evaluated in [22](8)[1]:

$$\Phi_{Conv.} = \frac{1}{2}\left[2\frac{\gamma(m,(\frac{T_{h4}}{\bar{\gamma}}))}{\Gamma(m)} + 2\frac{\gamma(m,(\frac{T_{h3}}{\bar{\gamma}}))}{\Gamma(m)} + \frac{\gamma(m,(\frac{T_{h2}}{\bar{\gamma}}))}{\Gamma(m)} + \frac{\gamma(m,(\frac{T_{h1}}{\bar{\gamma}}))}{\Gamma(m)}\right]. \tag{14}$$

As shown in Fig. 5, compared to the conventional adaptive modulation scheme, that of the MTART regime has an approximately 2.5dB gain for the throughput and has an approximately 3dB gain for the bandwidth-efficiency across a wide range of SNRs.

VI. Conclusions

In this contribution, the MTART scheme has been proposed for supporting delay-tolerant adaptive rate transmission of data over multihop links. A range of related formulas have been obtained for the OP and the throughput. We assumed that the adaptive modulation aided signals are transmitted over all hops experiencing i.i.d fading. Finally, our performance results show that the proposed MTART scheme has a significantly improved OP and throughput performance. Quantitatively, we have an approximately 3 dB gain in terms of the throughput attained, in comparison to the conventional adaptive modulation scheme. In our future research, we will investigate the

[1] Strictly speaking, the conventional adaptive modulation scheme cannot be applied based on our current assumptions due to the potentially unequal rate of each hops. For example, in a two-hop link, if the RN already has two packets stored and the RN-DN channel only allows us to transmit one packet, the two packets stored in the RN cannot be transmitted within one TS. However, we may relax the associated assumptions for the sake of finding the throughput of the conventional scheme. Let us assume that the transmission duration is adjustable, therefore, the RN can transmit the two packets to the DN in 2TSs. Then the corresponding throughput based on the CQ and the threshold can be evaluated from (14).

$$
\begin{aligned}
&C_{\{\widehat{r_1},\widehat{r_2}\}}\\
=&\sum_{l=1}^{2}\frac{|T_{h\{\widehat{r_1},\widehat{r_2}\}\oplus 1}\geq T_{h\gamma\oplus 1}|}{\ln 2\Gamma(m)}\left(\frac{m}{\gamma_h}\right)^{m}\sum_{j=0}^{|T_{h\{\widehat{r_1},\widehat{r_2}\}\oplus 1}\geq T_{h\gamma\oplus 1}|-1}(-1)^j\binom{|T_{h\{\widehat{r_1},\widehat{r_2}\}\oplus 1}\geq T_{h\gamma\oplus 1}|-1}{j}\sum_{k=0}^{j(m-1)}b_k^j\left(\frac{m}{\gamma_h}\right)^k\\
&\times NC(2,k+m-1,(j+1)m,T_{h1},T_{h\widehat{r_l}\oplus 1})\\
&+\sum_{l=1}^{2}\left(\frac{\gamma(m,T_{h\widehat{r_l}\oplus 1}\frac{m}{\gamma_h})}{\gamma(m)}\right)^{|\{\widehat{r_1},\widehat{r_2}\}>\widehat{r_l}|}\frac{|\{\widehat{r_1},\widehat{r_2}\}=\widehat{r_l}|}{\ln 2\Gamma(m)}\left(\frac{m}{\gamma_h}\right)^{m}\sum_{j=0}^{|\{\widehat{r_1},\widehat{r_2}\}=\widehat{r_l}|-1}(-1)^j\binom{|\{\widehat{r_1},\widehat{r_2}\}=\widehat{r_l}|-1}{j}\sum_{k=0}^{j(m-1)}b_k^j\left(\frac{m}{\bar{\gamma}}\right)^k\\
&\times NC(2,k+m-1,(j+1)m,T_{h\widehat{r_l}\oplus 1},\infty),
\end{aligned}
\tag{13}
$$

attainable MHD gain in conjunction with error-control coding as well as multi-hop ad-hoc networking.

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