Link Adaptation for Fixed Relaying with Untrusted Relays: Transmission Strategy Design and Performance Analysis

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***Abstract*—Wireless cooperative communication through link adaptation with untrusted relay assignment is considered. Using sharp channel codes in different transmission modes, reliability for destination and security in the presence of untrusted relays are provided through rate and power allocation. Scenarios with single available relay and opportunistic relaying in the presence of multiple relays are investigated. These scenarios are analyzed separately in terms of performance over Rayleigh fading channel for constant power and adaptive power transmission. In constant power case, closed form expressions for average spectral efficiency is derived through an effective approximation. Retaining the sum transmission power of source and relay unchanged, the performance of system is enhanced through power allocation. Numerical results reflect the effectiveness of the approximations for analytic performance evaluation when comparing to the simulation results.**

***Index Terms*—Cooperative communications, untrusted relay, link adaptation**

I. Introduction

Diversity and link adaptation are two techniques to facilitate high performance communications over wireless fading channels. Spatial diversity techniques are extensively studied in the literature. The space limitation is a serious challenge in multi-antenna transceivers. This in turn has lead the researchers towards distributed multiple antennas systems based on multiple cooperating nodes in wireless environment. The achievable rate of the relay channel was first presented in [1]. In cooperation for diversity, the relays are to assist a reliable data transmission from the source to the destination.

The cooperation of the source with a relay node may include a so-called service level trust, i.e., the relay node performs its expected function as a relay in the network. However, this cooperation may not include a data level trust, i.e., the relay is not supposed to extract useful information from the source destination communication. The information theoretic aspect of this problem is investigated in [2]-[4]. In [2] and [3] a three node network is considered, where system designer has the authority to compel relay to forward data toward destination for example by embedding the relaying capability in its hardware. But, the relay is not secure which means that it could potentially eavesdrop on the communication by decoding its received signal. An upper bound for the achievable secrecy rate in this setting is presented in [2].

Link adaptation for cooperative communications could highly improve the performance of the system. In [5], the capacity of the adaptive transmission over cooperative fading channel is considered for amplify-and-forward relaying, where three different adaptive techniques are considered. In [6], the performance of cooperative communication with relay selection and un-coded adaptive modulation is investigated. Authors in [7] propose a cross-layer approach to optimize the spectral efficiency of the relay channel using joint adaptive modulation and coding in conjunction with cooperative ARQ. Constructive approaches for (imperfect) physical layer security may be set up to ensure a reliable source destination communication, while maintaining a high probability of error for the eavesdropper. To this end, design of sharp punctured LDPC codes for which the bit error rate (BER) curve falls sharply from high BERs to very low BERs (steep waterfall region), is considered in [8]. Yet, adaptive transmission may be exploited to enhance the system performance both in terms of security and reliability. In this paper, a scheme for cooperative communication through link adaptation with untrusted relay assignment (LAURA) in constant power and adaptive power scenarios are proposed. A single cooperating relay is assumed or selected from the set of available untrusted relays. Transmission strategies are proposed in these settings for high spectral efficiency communication satisfying both reliablity and security constraints. A high probability of error requirement is considered for the relay to ensure that it can not interpret any useful data from its received signal. The performance of the proposed schemes is evaluated theoretically and also via simulation. The paper is organized as follows. Section II illustrates the system model and states the problem. In Section III, constant power LAURA scenario is considered, and then an analysis of its performance is presented. Section IV proposes an adaptive power LAURA scheme followed by an analysis of its performance. Section V presents the simulation and theoretical results for the proposed LAURA schemes. Section VI concludes the paper.

II. System Model and Problem Statement

A wireless communication system with one source node (S), one destination node (D) and a set of N_{R} available

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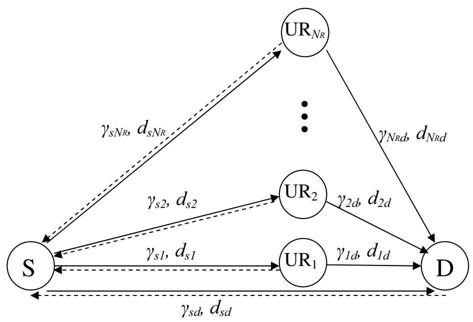

Fig. 1. Network topology

untrusted relay nodes, $\{\mathrm{UR}_1, \mathrm{UR}_2, ..., \mathrm{UR}_{N_\mathrm{R}}\}$, is considered (Fig. 1). There is a single cooperating relay that could either be preassigned or selected from the set of available relays (opportunistic relaying). The cooperation protocol is Amplify and Forward (AF). In the first phase of the transmission, the S node transmits signal x to the D node and relays. The received signal at the D node and at the UR_i node are respectively

$$y_{\mathrm{sd}} = h_{\mathrm{sd}}\, x + n_{\mathrm{d}} \tag{1}$$

$$y_{\mathrm{s}i} = h_{\mathrm{s}i}\, x + n_{\mathrm{s}i}, \tag{2}$$

where h_{sd}, and $h_{\mathrm{s}i}$ denote the Rayleigh fading coefficients between S and D nodes, and S and UR_i nodes, respectively. The noise is denoted at the relays as $n_{\mathrm{s}i}$ and at the D node as n_{d}. The cooperating relay amplifies the received signal and transmits it to the D node in the second phase of cooperation. The received signal at the D node from the UR_i node is

$$y_{i\mathrm{d}} = G_i\, h_{i\mathrm{d}}\, y_{\mathrm{s}i} + n'_{\mathrm{d}}, \tag{3}$$

where G_i is the UR_i node amplifier gain, and, $h_{i\mathrm{d}}$ and n'_{d} are Rayleigh fading coefficients from UR_i node to the D node and noise at the D node, respectively.

The S-D, S-UR_i, UR_i-D channels, for $1 \leq i \leq N_\mathrm{R}$, are independent Rayleigh fading channels with SNRs of γ_{sd}, $\gamma_{\mathrm{s}i}$ and $\gamma_{i\mathrm{d}}$, respectively. These SNRs are exponentially distributed with parameters $\frac{1}{\bar{\gamma}_{\mathrm{sd}}}$, $\frac{1}{\bar{\gamma}_{\mathrm{s}i}}$ and $\frac{1}{\bar{\gamma}_{i\mathrm{d}}}$, and, probability density functions of $f_{\mathrm{sd}}(\gamma_{\mathrm{sd}})$, $f_{\mathrm{s}i}(\gamma_{\mathrm{s}i})$, and $f_{i\mathrm{d}}(\gamma_{i\mathrm{d}})$, respectively. These instantaneous SNRs as channel state information of the three channels are assumed known at the beginning of each frame interval at the S node. Assuming Maximum Ratio Combining (MRC) of signal received from S and UR_i node at the D node, the equivalent SNR of AF relaying protocol is [9]

$$\gamma_{\mathrm{eq}}^{(i)} = \frac{S_\mathrm{s}}{S}\gamma_{\mathrm{sd}} + \frac{\frac{S_\mathrm{s}}{S}\gamma_{\mathrm{s}i}\,\frac{S_i}{S}\gamma_{i\mathrm{d}}}{\frac{S_\mathrm{s}}{S}\gamma_{\mathrm{s}i} + \frac{S_i}{S}\gamma_{i\mathrm{d}} + 1}, \tag{4}$$

where S_s and S_i are the normalized transmission power of source and relay, respectively. For the sake of tractability of theoretical performance analysis in some cases, we may use an upper bound on $\gamma_{\mathrm{eq}}^{(i)}$ as

$$\gamma_{\mathrm{eq,u}}^{(i)} = \frac{S_\mathrm{s}}{S}\gamma_{\mathrm{sd}} + \min\left(\frac{S_\mathrm{s}}{S}\gamma_{\mathrm{s}i}, \frac{S_i}{S}\gamma_{i\mathrm{d}}\right). \tag{5}$$

This bound is frequently used in the literature [5], [6].

The cooperating relay is assumed trusted at the *service level* and untrusted at the *data level*. Service level trust encompasses true channel state information (CSI) feedback, power adaptation according to source schedule and forwarding the amplified version of received signal without modification. Non-cooperating relays are also service level trusted, i.e., they are only capable of listening to the transmitted signal in the first half of transmission interval as they are expected. Since, all relays are data level untrusted, we have a security constraint for cooperating and non-cooperating relays, i.e., transmitter plans to prevent all relay nodes from extracting useful information from their received signal.

We use the set of N transmission modes (TM) each resulted from a combination of modulation and coding. These TMs comprise rates $\{R_1, R_2, ..., R_N\}$ bits per symbol, where $R_n > R_{n-1}$. We can express the BER of TM n as an approximated function of received SNR, γ, through curve fitting by

$$\mathrm{BER}_n(\gamma) = \begin{cases} 0.5\, e^{-p_n \gamma^{q_n}} & \text{if } \gamma < \gamma_{lh}^n \\ \dfrac{a_n}{\left(1 + e^{c_n(\gamma - b_n)}\right)^{d_n}} & \text{if } \gamma \geq \gamma_{lh}^n \end{cases}$$

where p_n, q_n, a_n, b_n, c_n and d_n are the approximation fitting coefficients. The expression for the second part is a modification of what is proposed in [10]. The inverse of $\mathrm{BER}_n(\gamma)$ describing received SNR as a function of BER is given by

$$\Gamma_n(P_e) = \begin{cases} \left(\ln(\dfrac{0.5}{P_e})\Big/ p_n\right)^{\frac{1}{q_n}} & \text{if } P_e > \mathrm{BER}_n(\gamma_{lh}^n) \\ \dfrac{1}{c_n}\ln\left[\left(\dfrac{a_n}{P_e}\right)^{1/d_n} - 1\right] + b_n & \text{if } P_e \leq \mathrm{BER}_n(\gamma_{lh}^n) \end{cases} \tag{6}$$

The objective is to maximize the spectral efficiency of the system while providing both security against eavesdropping of untrusted relays and reliability for destination. These two requirements are expressed as follows

$$\begin{aligned} &\text{C1.}\quad \mathrm{BER}_i \geq \mathrm{BER}_{\mathrm{tgt}}^{\mathrm{r}} \;\; \text{for } 1 \leq i \leq N_\mathrm{R} \\ &\text{C2.}\quad \mathrm{BER}_\mathrm{d} \leq \mathrm{BER}_{\mathrm{tgt}}^{\mathrm{d}}, \end{aligned} \tag{7}$$

where BER_i is the BER of UR_i node and BER_d is the BER of the D node applying MRC. The average spectral efficiency is expressed as

$$\eta = \sum_{n=1}^{N} \frac{R_n}{2}\Pr(\mathrm{TM} = n), \tag{8}$$

where $\Pr(\mathrm{TM} = n) = P_n$ is the probability of selecting TM number n for transmission. The factor $1/2$ multiplied by R_n is due to the half-duplex cooperative transmission.

III. Constant Power LAURA

A general scenario for constant power (CP) link adaptation with untrusted relay assignment is considered in this section. The source and relay powers are fixed at $S_\mathrm{s} = S$ and $S_i = S$.

A. Problem Definition and Solution

Considering $R_n^{(i)}$ to be the transmission rate with $\mathrm{TM} = n$ through cooperating with UR_i node, the problem of CP-LAURA is formulated as follows

$$\begin{aligned} &\max_{\substack{n\in\{1,2,\dots,N\}\\ i\in\{1,\dots,N_\mathrm{R}\}}} \quad R_n^{(i)} \\ \text{s.t.} \quad & \text{C1.} \quad \mathrm{BER}_j \geq \mathrm{BER}_\mathrm{tgt}^\mathrm{r} \,\text{for}\, 1 \leq j \leq N_\mathrm{R} \\ & \text{C2.} \quad \mathrm{BER}_\mathrm{d} \leq \mathrm{BER}_\mathrm{tgt}^\mathrm{d} \end{aligned} \tag{9}$$

The security constraint C1 is to hold for all possible relays in the network. Given this fact and considering the reliability constraint C2, a larger equivalent SNR at the D node allows for transmission with a higher rate. Therefore, the optimal relay selection according to problem (9) is to identify the relay that provides the maximum equivalent SNR at the D node. Thus, the cooperating relay number is $i^* = \arg\max_i \gamma_\mathrm{eq}^{(i)}$, and Algorithm 1 yields the optimal solution of this problem.

Algorithm 1: Constant power LAURA

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1) Select $i^* = \arg\max_i \gamma_\mathrm{eq}^{(i)}$
2) Select $n = N$.
3) If $n = 0$ or C1 in (9) does not hold go to outage mode, i.e., do not transmit.
4) If C2 in (9) is satisfied, set $\mathrm{TM} = n$ and exit; else $n = n - 1$ and go to step 3.

B. Performance Analysis

Now, we analyze the performance of CP-LAURA by computing its average spectral efficiency. To this end and according to (8), we merely need to calculate the probability of selecting each TM. The event that relay i^* satisfies the reliability constraint corresponds to the event that there is at least one relay that can satisfy this constraint. Then, the event that TM number n satisfies both security and reliability requirements is denoted by A_n. For CP-LAURA, we have

$$A_n = \bigcap_{i=1}^{N_\mathrm{R}} \gamma_{si} \leq \Gamma_n^\mathrm{r} \cap \bigcup_{i=1}^{N_\mathrm{R}} \gamma_\mathrm{eq}^{(i)} \geq \Gamma_n^\mathrm{d}, \tag{10}$$

where based on (6), $\Gamma_n^\mathrm{r} \triangleq \Gamma_n(\mathrm{BER}_\mathrm{tgt}^\mathrm{r})$ and $\Gamma_n^\mathrm{d} \triangleq \Gamma_n(\mathrm{BER}_\mathrm{tgt}^\mathrm{d})$. Then, for CP-LAURA the probability of $\mathrm{TM} = m$ is

$$\begin{aligned} P_m^\mathrm{CP} =& \Pr\left(A_m \cap \bigcap_{n=m+1}^{N} A_n^\mathrm{c}\right) \\ =& \Pr\left(\left\{\bigcap_{i=1}^{N_\mathrm{R}} \gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \bigcup_{i=1}^{N_\mathrm{R}} \gamma_\mathrm{eq}^{(i)} \geq \Gamma_m^\mathrm{d}\right\} \cap \bigcap_{i=1}^{N_\mathrm{R}} \gamma_\mathrm{eq}^{(i)} < \Gamma_{m+1}^\mathrm{d}\right) \\ &- \Pr\left(\left\{\bigcap_{i=1}^{N_\mathrm{R}} \gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \gamma_\mathrm{eq}^{(i)} < \Gamma_{m+1}^\mathrm{d}\right\} \cap \bigcup_{i=1}^{N_\mathrm{R}} \gamma_\mathrm{eq}^{(i)} \geq \Gamma_m^\mathrm{d}\right) \\ =& \Pr\left(\bigcap_{i=1}^{N_\mathrm{R}} \gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \gamma_\mathrm{eq}^{(i)} < \Gamma_{m+1}^\mathrm{d}\right) \\ &- \Pr\left(\bigcap_{i=1}^{N_\mathrm{R}} \gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \gamma_\mathrm{eq}^{(i)} < \Gamma_m^\mathrm{d}\right). \end{aligned} \tag{11}$$

Since different relay channels are independent, given γ_sd, $\gamma_\mathrm{eq}^{(i)}$ is independent of $\gamma_\mathrm{eq}^{(j)}$ for $i \neq j$. Then

$$\begin{aligned} P_m^\mathrm{CP} =& \mathbf{E}_{\gamma_\mathrm{sd}}\Big\{ \prod_{i=1}^{N_\mathrm{R}} \Pr\left(\gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \gamma_\mathrm{eq}^{(i)} < \Gamma_{m+1}^\mathrm{d} | \gamma_\mathrm{sd}\right) \\ &- \prod_{i=1}^{N_\mathrm{R}} \Pr\left(\gamma_{si} \leq \Gamma_m^\mathrm{r} \cap \gamma_\mathrm{eq}^{(i)} < \Gamma_m^\mathrm{d} | \gamma_\mathrm{sd}\right) \Big\}, \end{aligned} \tag{12}$$

where operator $\mathbf{E}_{\gamma_\mathrm{sd}}\{\cdot\}$ denotes expected value over γ_sd. Using the upper bound for equivalent SNR in (5), a closed form expression for the TM probability is obtained as follows

$$\begin{aligned} P_m^\mathrm{CP} =& \\ \mathbf{E}_{\gamma_\mathrm{sd}} & \Bigg\{ \prod_{i=1}^{N_\mathrm{R}} \left(1 - e^{-\frac{\Gamma_m^\mathrm{r}}{\bar{\gamma}_{si}}} - \left[e^{-\frac{\left[\Gamma_m^\mathrm{d} - \gamma_\mathrm{sd}\right]^+}{\bar{\gamma}_{si}}} - e^{-\frac{\Gamma_m^\mathrm{r}}{\bar{\gamma}_{si}}} \right]^+ . \, e^{-\frac{\left[\Gamma_m^\mathrm{d} - \gamma_\mathrm{sd}\right]^+}{\bar{\gamma}_{id}}} \right) \\ - \prod_{i=1}^{N_\mathrm{R}} & \left(1 - e^{-\frac{\Gamma_m^\mathrm{r}}{\bar{\gamma}_{si}}} - \left[e^{-\frac{\left[\Gamma_{m+1}^\mathrm{d} - \gamma_\mathrm{sd}\right]^+}{\bar{\gamma}_{si}}} - e^{-\frac{\Gamma_m^\mathrm{r}}{\bar{\gamma}_{si}}} \right]^+ . \, e^{-\frac{\left[\Gamma_{m+1}^{d} - \gamma_\mathrm{sd}\right]^+}{\bar{\gamma}_{id}}} \right) \Bigg\}, \end{aligned}$$

where $[x]^+$ denotes $\max(x, 0)$.

IV. Adaptive Power LAURA

For adaptive power (AP) link adaptation with untrusted relay assignment, we retain the maximum power consumption of the system unchanged and try to maximize the transmission rate by power adaptation. A general scenario is considered in which a relay is selected among a set of untrusted relays.

A. Problem Definition and Solution

For AP-LAURA, the problem of instantaneous rate maximization is expressed as follows

$$\begin{aligned} &\max_{n\in\{1,2,\dots,N\}} \max_{\substack{S_\mathrm{s}, S_i \\ i\in\{1,\dots,N_\mathrm{R}\}}} \quad R_n^{(i)} \\ \text{s.t.} \quad & \text{C1.} \quad \mathrm{BER}_j \geq \mathrm{BER}_\mathrm{tgt}^\mathrm{r} \,\text{for}\, 1 \leq j \leq N_\mathrm{R} \\ & \text{C2.} \quad \mathrm{BER}_\mathrm{d} \leq \mathrm{BER}_\mathrm{tgt}^\mathrm{d} \\ & \text{C3.} \quad S_\mathrm{s} + S_i \leq 2S. \end{aligned} \tag{13}$$

In the followings, we first derive the optimal power allocation for cooperating with UR_i node and considering only the security and power constraints. This corresponds to the inner maximization in (13). Next, using the results we propose an algorithm to solve problem (13).

As discussed in Section III, noting C2, a larger γ_eq yields a higher rate. Thus, the inner maximization is equivalent to

$$\begin{aligned} &\max_{\substack{S_\mathrm{s}, S_i \\ i\in\{1,\dots,N_\mathrm{R}\}}} \quad \gamma_\mathrm{eq}^{(i)} \\ \text{s.t.} \quad & \text{C1.} \quad \frac{S_\mathrm{s}}{S} \leq \frac{\Gamma_n^\mathrm{r}}{\gamma_{s\tilde{i}}} \\ & \text{C2.} \quad S_\mathrm{s} + S_i \leq 2S, \end{aligned} \tag{14}$$

where $\tilde{i} = \arg\max_i \gamma_{si}$. It can be shown that $\gamma_\mathrm{eq}^{(i)}$ is a concave function of S_s and S_i. To this end, three conditions should hold [11, Appendix 1]: $(\partial^2 \gamma_\mathrm{eq}^{(i)} / \partial S_i^2) \leq 0$, $(\partial^2 \gamma_\mathrm{eq}^{(i)} / \partial S_\mathrm{s}^2) \leq 0$ and

$(\partial^2\gamma_{\text{eq}}^{(i)}/\partial S_i^2)(\partial^2\gamma_{\text{eq}}^{(i)}/\partial S_{\text{s}}^2) - [(\partial^2\gamma_{\text{eq}}^{(i)}/\partial S_{\text{s}}\partial S_i)]^2 \leq 0$. It can be easily shown that these three conditions hold for $\gamma_{\text{eq}}^{(i)}$. Thus, KKT condition gives the optimal solution to this problem.

The constraint C2 in (14) is released by setting $S_i = 2S - S_{\text{s}}$. Then, for cooperation through UR_i node we have

$$\frac{\partial\gamma_{\text{eq}}^{(i)}}{\partial S_{\text{s}}} = 0, \tag{15}$$

that yields $S_{\text{s}} = \frac{-\theta_i - \sqrt{\theta_i^2 - 4\mu_i\rho_i}}{2\mu_i} \triangleq S_{\text{s},i}^*$, where

$$\begin{aligned}
\mu_i &= \gamma_{i\text{d}}^2(\gamma_{\text{s}i} + \gamma_{\text{sd}}) + \gamma_{\text{s}i}^2(\gamma_{\text{sd}} - \gamma_{i\text{d}}) - 2\gamma_{\text{sd}}\gamma_{i\text{d}}\gamma_{\text{s}i}\\
\theta_i &= 2[\gamma_{\text{s}i}(\gamma_{\text{sd}} - \gamma_{i\text{d}} + 2\gamma_{i\text{d}}\gamma_{\text{sd}}) - 2\gamma_{i\text{d}}^2(\gamma_{\text{s}i} + \gamma_{\text{sd}}) - \gamma_{i\text{d}}\gamma_{\text{sd}}]\\
\rho_i &= \gamma_{\text{sd}} + 4\gamma_{i\text{d}}^2(\gamma_{\text{s}i} + \gamma_{\text{sd}}) + 4\gamma_{i\text{d}}\gamma_{\text{sd}} + 2\gamma_{i\text{d}}\gamma_{\text{s}i}.
\end{aligned}$$

Then, the optimal transmission power of S node cooperating with UR_i node is

$$S_{\text{s},n,i}^{\text{opt}} = \min(S_{\text{s},i}^*, 2S, S\frac{\Gamma_n^{\text{r}}}{\gamma_{\text{s}\tilde{i}}}). \tag{16}$$

Given the above results, Algorithm 2 presents a joint relay selection and rate adaptation strategy to solve problem (13).

Algorithm 1:Adaptive power LAURA

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1) Select $n = N$.
2) If $n = 0$ then go to outage mode and exit.
3) Select relay as $i_n^* = \arg\max_i \left\{ \left[\gamma_{\text{eq}}^{(i)}\right]_{S_{\text{s}} = S_{\text{s},n,i}^{\text{opt}}} \right\}$.
4) Set $S_{\text{s}} = \min(S_{\text{s}}^{*,i_n^*}, 2S, S\frac{\Gamma_n^{\text{r}}}{\gamma_{\text{s}\tilde{i}}})$.
5) If C2 in (13) is satisfied, set $\text{TM} = n$ and exit; else $n = n - 1$ and go to step 2.

B. Performance Analysis

Now, we analyze the performance of AP-LAURA by computing its average spectral efficiency. For tractability of the analysis, we address the cases with single available relay (SR) and multiple available relays (MR), separately.

1) SR-AP-LAURA: The constraint C2 in (13) is equivalent to

$$\gamma_{\text{sd}} \geq \left[\frac{S}{S_{\text{s}}}\left(\Gamma_n^{\text{d}} - \frac{\frac{S_{\text{s}}}{S}\gamma_{\text{sr}}\frac{2S - S_{\text{s}}}{S}\gamma_{\text{rd}}}{\frac{S_{\text{s}}}{S}\gamma_{\text{sr}} + \frac{2S - S_{\text{s}}}{S}\gamma_{\text{rd}} + 1}\right)\right]_{S_{\text{s}} = S_{\text{s},n}^{\text{opt}}}. \tag{17}$$

Noting that $S_{\text{s},n}^{\text{opt}}$ is a function of γ_{sd}, (17) can be numerically expressed as $\gamma_{\text{sd}} \geq \gamma_{\text{sd}}^{\min,n}$. Note that index r stands for the only available relay. For the presented transmission strategy, the probability of A_n is (see Section III for definition)

$$\begin{aligned}
\Pr(A_n) &= \Pr\left(\gamma_{\text{eq}}\Big|_{S_{\text{s}} = S_{\text{s}}^{\text{opt}}} \geq \Gamma_n^{\text{d}}\right)\\
&= \mathbf{E}_{\gamma_{\text{rd}},\gamma_{\text{sr}}}\left\{\Pr\left(\gamma_{\text{sd}} \geq \gamma_{\text{sd}}^{\min,n}|\gamma_{\text{rd}},\gamma_{\text{sr}}\right)\right\}\\
&= \mathbf{E}_{\gamma_{\text{rd}},\gamma_{\text{sr}}}\left\{e^{\frac{-\left[\gamma_{\text{sd}}^{\min,n}\right]^+}{\bar{\gamma}_{\text{sd}}}}\right\}.
\end{aligned}$$

The probability of selecting TM m is

$$\begin{aligned}
P_m^{\text{SR-AP}} &= \Pr\left(A_m \cap \bigcap_{n=m+1}^{N} A_n^{\text{c}}\right) = \Pr\left(\bigcup_{n=m}^{N} A_n\right) - \Pr\left(\bigcup_{n=m+1}^{N} A_n\right)\\
&= \mathbf{E}_{\gamma_{\text{rd}},\gamma_{\text{sr}}}\left\{\Pr\left(\bigcup_{n=m}^{N} A_n|\gamma_{\text{rd}},\gamma_{\text{sr}}\right)\right\}\\
&\quad - \mathbf{E}_{\gamma_{\text{rd}},\gamma_{\text{sr}}}\left\{\Pr\left(\bigcup_{n=m+1}^{N} A_n|\gamma_{\text{rd}},\gamma_{\text{sr}}\right)\right\}\\
&= \mathbf{E}_{\gamma_{\text{rd}},\gamma_{\text{sr}}}\left\{\Pr\left(A_{\tilde{n}_m}|\gamma_{\text{rd}},\gamma_{\text{sr}}\right) - \Pr\left(A_{\tilde{n}_{m+1}}|\gamma_{\text{rd}},\gamma_{\text{sr}}\right)\right\},
\end{aligned}$$

where

$$\tilde{n}_m(\gamma_{\text{rd}},\gamma_{\text{sr}}) = \arg\min_{n\in\{m,\ldots,N\}}\left(\left[\gamma_{\text{sd}}^{min,n}\right]^+\right).$$

2) MR-AP-LAURA: For multiple available relays, The constraint C2 in (13) for cooperation through UR_i node is expressed as the following event

$$A_n^i \triangleq \gamma_{\text{eq}}^{(i)} = \left[\frac{S_{\text{s}}}{S}\gamma_{\text{sd}} + \frac{\frac{S_{\text{s}}}{S}\gamma_{\text{s}i}\frac{2S - S_{\text{s}}}{S}\gamma_{i\text{d}}}{\frac{S_{\text{s}}}{S}\gamma_{\text{s}i} + \frac{2S - S_{\text{s}}}{S}\gamma_{i\text{d}} + 1}\right]_{S_{\text{s}} = S_{\text{s},n,i}^{\text{opt}}} \geq \Gamma_n^{\text{d}}. \tag{18}$$

For the presented transmission strategy in Algorithm 1, the event that TM number n satisfies both security and reliability requirements is denoted by A_n and its probability is

$$\begin{aligned}
\Pr(A_n) &= \Pr\left(\bigcup_{i=1}^{N_{\text{R}}} A_n^i\right) = 1 - \Pr\left(\bigcap_{i=1}^{N_{\text{R}}} \left(A_n^i\right)^{\text{c}}\right)\\
&= 1 - \mathbf{E}_{\gamma_{\text{sd}},\gamma_{\text{s}\tilde{i}}}\left\{\Pr\left(\bigcap_{i=1}^{N_{\text{R}}} \left(A_n^i\right)^{\text{c}}|\gamma_{\text{sd}},\gamma_{\text{s}\tilde{i}}\right)\right\},\\
&= 1 - \mathbf{E}_{\gamma_{\text{sd}},\gamma_{\text{s}\tilde{i}}}\left\{\prod_{i=1}^{N_{\text{R}}}\left[1 - \Pr\left(\gamma_{\text{eq}}^{(i)} \geq \Gamma_n^{\text{d}}|\gamma_{\text{sd}},\gamma_{\text{s}\tilde{i}}\right)\right]\right\}.
\end{aligned} \tag{19}$$

The last equality in (19) results from independence of A_n^i and A_n^j for $i \neq j$ given γ_{sd} and $\gamma_{\text{s}\tilde{i}}$. The probability of selecting TM m is

$$\begin{aligned}
P_m^{\text{MR-AP}} &= \Pr\left(\bigcup_{n=m}^{N} A_n\right) - \Pr\left(\bigcup_{n=m+1}^{N} A_n\right)\\
&= \mathbf{E}\left\{\mathbf{I}\left(A_{\tilde{n}_m}\right) - \mathbf{I}\left(A_{\tilde{n}_{m+1}}\right)\right\},
\end{aligned} \tag{20}$$

where $\mathbf{I}(\cdot)$ is the indicator function, and

$$\tilde{n}_m(\gamma_{\text{eq}}^{(i)},\gamma_{\text{s}\tilde{i}}) = \arg\min_{n\in\{m,\ldots,N\}}\left(\gamma_{\text{eq}}^{(i)} \geq \Gamma_n^{\text{d}} \mid S_{\text{s}} = S_{\text{s},n,i}^{\text{opt}}\right). \tag{21}$$

Here, in order to facilitate the analysis we introduce an approximation for which the effectiveness is shown in Section V, i.e., to consider

$$\tilde{n}_m(\gamma_{\text{eq}}^{(i)},\gamma_{\text{s}\tilde{i}}) \approx m. \tag{22}$$

Then, the probability of TM m is

$$P_m^{\text{MR-AP}} = \Pr\left(A_m\right) - \Pr\left(A_{m+1}\right). \tag{23}$$

The conditional PDF of $\gamma_{\text{s}i}$ and $\gamma_{\text{s}\tilde{i}}$ is required to compute $P_m^{\text{MR-AP}}$ that is derived in Appendix A.

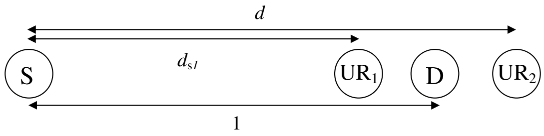

Fig. 2. One and two available untrusted relays topology

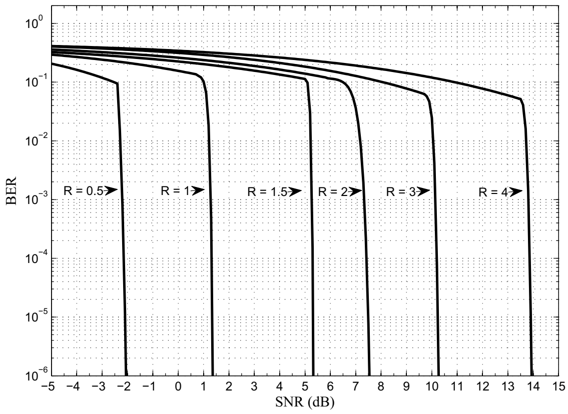

Fig. 3. BER curves for 6 transmission modes and their corresponding rates

TABLE I
TRANSMISSION MODES FOR AMC SCHEME AND THEIR CORRESPONDING FITTING PARAMETERS

Mode	1	2	3	4	5	6
modulation	BPSK	4-QAM	8-QAM	8-QAM	16-QAM	32-QAM
coding rate	1/2	1/2	1/2	2/3	3/4	4/5
rate: R_n	1/2	1	3/2	2	3	4
p_n	2.971	1.168	0.8	0.651	0.463	0.38
q_n	1.05	0.682	0.538	0.586	0.672	0.575
a_n	1.549	0.132	0.138	0.1187	0.063	0.065
b_n	0.616	1.432	3.483	6.191	10.37	24.087
c_n	41.9	34.85	20.03	3.522	5.13	2.209
d_n	16.81	104.7	48.83	75.990	6.773	6.5

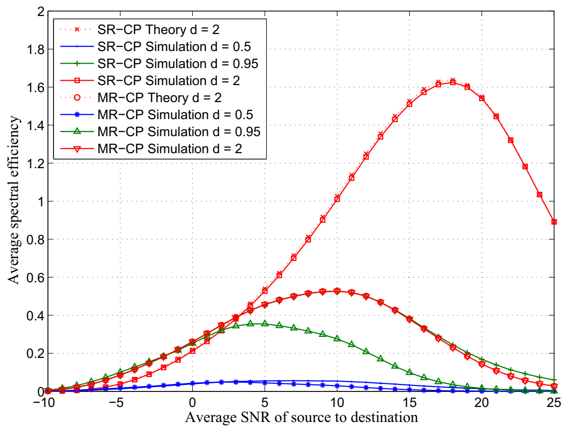

Fig. 4. Average spectral efficiency of CP-LAURA for different scenarios

V. PERFORMANCE EVALUATION

A. Experiment Setup

Fig. 2 illustrates the system topology for one and two available relays. We consider average SNR of each channel proportional to $\frac{1}{l^{\alpha}}$, due to path loss, where l denotes the distance between the two parties (α is set to 4 in this paper). Without loss of generality we consider the distance between S node and D node normalized to 1. Both relays are located on the connecting line of S and D nodes.In one relay scenarios, the distance from S and UR_1 nodes is d. In two relays scenario, UR_1 node is fixed at the distance 0.95 and the UR_2 is placed in different distances from S node as depicted in Fig. 2. In all figures, $\mathrm{BER}^{\mathrm{r}}_{\mathrm{tgt}}$ and $\mathrm{BER}^{\mathrm{d}}_{\mathrm{tgt}}$ are set to 0.1 and 10^{-6}, respectively.

The TMs used for performance analysis could be any set of possible channel coding and modulation. The suggestion is to use sharp channel codes to obtain sharp BER curves for TMs. The set of LDPC codes of DVB-S2 standard offer this characteristic. These channel codes in conjunction with large constellations yield the BER curves depicted in Fig. 3. The approximation coefficients are determined in Table I for each TM.

B. Numerical Results

Figure 4 depicts the average spectral efficiency of CP-LAURA scheme in different scenarios. In horizontal axis, the average SNRs of S-D link and also, for a fixed d, S-UR_i links grow from left to right. It is observed that increasing average SNR of S-D link leads to declination in average spectral efficiency after a specific value. The reason is limitation of the number of TMs. If there is a TM that could satisfy security constraint in high SNRs, then the declination occurs later in higher average SNR of S-D channel. Another observation is that increasing the number of available relays decreases average spectral efficiency for high average SNRs and increases it for low average SNRs. The reason is that for high average SNRs the larger the number of available relays, the more likely a relay exists with high receiving SNR. This leads the source not to transmit for CP scenarios (outage mode). However, for low average SNRs in MR scenarios, the advantage of selecting best relay outweighs the disadvantage of restriction via security requirement. For $d = 2$ the theoretical results, that is calculated through approximation (5), are shown and prove its effectiveness.

Figure 5 depicts the average spectral efficiency of AP-LAURA scheme for different scenarios. Obviously power adaptation fixes the unexpected outages issue, due to the security constraint, by reducing transmission power of S node, and devoting the rest to the relay. The AP-LAURA scheme also outperforms CP-LAURA in terms of peak performance. This can be easily observed by comparing Fig. 4 and Fig. 5 for the same scenarios that further illustrates the necessity of power adaptation for LAURA. In MR-AP scenarios for small average SNRs of S-D channel, the approximation (22) works well. However, for larger SNRs, there is a minor difference between simulation and approximate theoretical result.

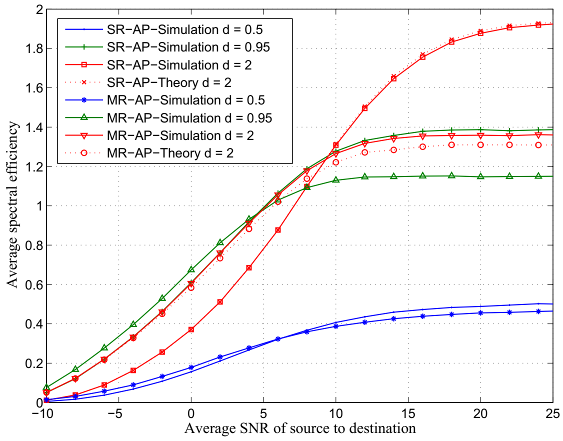

Fig. 5. Average spectral efficiency of AP-LAURA for different scenarios

VI. Conclusion

In this paper, a link adaptation and relay selection approach for cooperative communication with data level untrusted relays is proposed. Performance of this approach is analyzed for constant power as well as adaptive power rate adaptation and relay selection theoretically and through simulations. The comparison of constant and adaptive power schemes suggests the advantage of power adaptation for both source and cooperating relays. The future works include considering the non-cooperative behavior of relays such as using MRC, in which the relays should be treated as eavesdropper, and untrue CSI feed back by the relays.

Acknowledgments

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Appendix A

In this section we derive the joint and conditional PDF of $\gamma_{s\tilde{i}}, \gamma_{si}$. The joint cumulative distribution function of these two variables is given by

$$F_{\gamma_{s\tilde{i}},\gamma_{si}}(x,y) = \Pr(\max_j \gamma_{sj} < x, \gamma_{si} < y) = \prod_{\substack{j=1\\ j\neq i}}^{N_R} \left(1 - e^{-\frac{x}{\bar{\gamma}_{sj}}}\right) \cdot \left[\left(1 - e^{-\frac{x}{\bar{\gamma}_{si}}}\right)\mathcal{U}(y-x) + \left(1 - e^{-\frac{y}{\bar{\gamma}_{si}}}\right)\mathcal{U}(x-y)\right],$$

where $\mathcal{U}(\cdot)$ denotes the unit step function. Then, the joint probability density function of $\gamma_{s\tilde{i}}, \gamma_{si}$ is

$$\begin{aligned} f_{\gamma_{s\tilde{i}},\gamma_{si}}(x,y) &= \frac{\partial^2 F_{\gamma_{s\tilde{i}},\gamma_{si}}(x,y)}{\partial x \partial y} \\ &= \sum_{l\neq i} \frac{1}{\bar{\gamma}_{sl}} e^{-\frac{x}{\bar{\gamma}_{sl}}} \prod_{\substack{j\neq l\\ j\neq i}} \left(1 - e^{-\frac{x}{\bar{\gamma}_{sj}}}\right) \left[\frac{1}{\bar{\gamma}_{si}} e^{-\frac{y}{\bar{\gamma}_{si}}} \mathcal{U}(x-y)\right] \\ &\quad + \prod_{j\neq i} \left(1 - e^{-\frac{x}{\bar{\gamma}_{sj}}}\right) \frac{1}{\bar{\gamma}_{si}} e^{-\frac{x}{\bar{\gamma}_{si}}} \delta(y-x) \\ &\triangleq A_i(x) \left[\frac{1}{\bar{\gamma}_{si}} e^{-\frac{y}{\bar{\gamma}_{si}}} \mathcal{U}(x-y)\right] + B_i(x)\delta(y-x), \end{aligned}$$

where $\delta(\cdot)$ denotes the unit impulse function. The PDF of $\gamma_{s\tilde{i}}$ is simply

$$f_{\gamma_{s\tilde{i}}}(x) = \sum_{l=1}^{N_R} \frac{1}{\bar{\gamma}_{sl}} e^{-\frac{x}{\bar{\gamma}_{sl}}} \prod_{j\neq l} \left(1 - e^{-\frac{x}{\bar{\gamma}_{sj}}}\right) \triangleq C(x). \tag{24}$$

The PDF of γ_{si} given $\gamma_{s\tilde{i}}$ is then

$$\begin{aligned} f_{\gamma_{si}|\gamma_{s\tilde{i}}}(y|x) &= \frac{f_{\gamma_{s\tilde{i}},\gamma_{si}}(x,y)}{f_{\gamma_{s\tilde{i}}}(x)} \\ &= \frac{A_i(x)}{C(x)} \left[\frac{1}{\bar{\gamma}_{si}} e^{-\frac{y}{\bar{\gamma}_{si}}} \mathcal{U}(x-y)\right] + \frac{B_i(x)}{C(x)} \delta(y-x). \end{aligned} \tag{25}$$

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