Adaptive Resource Allocation for Secure Two-Hop Relaying Communication

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***Abstract*— In this paper, we develop novel transmission schemes for secure dual-hop Alice–Ray–Bob relaying communication over fading channels in the presence of a passive eavesdropper (Eve). To control the risk of secrecy outage under unknown eavesdropper channel conditions, we impose secrecy constraint in terms of maximum allowable secrecy outage probability. We study the throughput–optimal buffer-aided adaptive relaying problem for two scenarios: 1) fixed (Alice and Ray) power allocation and 2) adaptive power allocation. The resulting constrained optimization problems are solved using Lagrangian approach and convex optimization. In each frame, either Alice or Ray or neither is scheduled for transmission depending on the main (Alice–Ray and Ray–Bob) channel conditions. Since the transmission schemes can result in unboundedly large (queuing) delay at Ray's buffer, we next study the transmission schemes guaranteeing the bounded average delay. The optimal transmission problem is formulated as an infinite horizon average reward constrained Markov decision process. Subsequently, by relying on a novel state value function approach, we show that in each frame, the solution can be obtained by solving a concave maximization problem, taking into account both the main channel conditions and the buffer state. An online transmission algorithm is developed to iteratively update the state value function, which converges to the optimal solution without requiring *a-priori* statistical information on the fading channels. The simulation results demonstrate the effectiveness of the proposed schemes over benchmark schemes under various secrecy constraints and signal-to-noise power ratio regimes.**

***Index Terms*— Delay-constrained communication, dual-hop relaying, resource allocation, secrecy outage probability, wiretap channel.**

I. Introduction

RESEARCH on secure wireless communication falls into broad categories of network layer cryptography [2], physical layer security [3], or a combination of both [4]. The former assumes that the physical layer provides error-free data links, in which security depends on encryption. However, different challenges in terms of key exchange and distribution are imposed, especially under dynamic network configurations. In physical layer security, the strategy is to exploit physical layer characteristics of wireless channels, such as interference, noise, and wireless fading to protect the secret data from eavesdropping without the need of encryption. The security measure is *secrecy capacity* introduced in [5] for a 3-node wiretap model Alice–Bob–Eve. More specifically, secrecy capacity characterizes the maximum transmission rate from transmitter (Alice) to receiver (Bob), below which an eavesdropper (Eve) is unable to obtain any information. Subsequent studies on secrecy capacity of a wiretap model over fading channels have been carried out in [6]–[8]. To compute secrecy capacity and enable secure encoding, these works assume that instantaneous channel state information (CSI) of both main Alice–Bob and eavesdropper Alice–Eve channels is available at Alice. However, in many practical scenarios, the instantaneous CSI of a passive Eve is very unlikely to be unveiled at Alice, and thus it is more realistic to assume that only statistical CSI of Alice–Eve channel (in addition to the instantaneous CSI of Alice–Bob channel) is available at Alice [9]–[15]. For transmission over quasi-static fading channels under such CSI assumption, a secrecy outage event is deemed to occur when an instantaneous secrecy capacity is less than a target secrecy rate, and the secrecy outage probability (SOP) measures the probability of the secrecy outage event [10], [11], [13] etc.

Consider the wiretap fading model Alice–Bob–Eve to support secure communications with small SOP. Unless the Alice–Eve channel is (much) weaker than the Alice–Bob channel, the small SOP requirement can hardly be satisfied. This motivates us to deploy a relay (Ray) together with dual-hop relaying protocols to enhance secure Alice–Bob communication. By placing Ray into an appropriate location between Alice and Bob, due to shorter communication distances, the main channels (i.e., Alice–Ray and Ray–Bob) can be made stronger than the eavesdropper channels (i.e., Alice–Eve and Ray–Eve), and thus lessening the SOP and/or increasing the secrecy rate. We consider scenario where Ray acts purely as a trusted relay to forward information from Alice to Bob, for example, see [16]–[24] and references therein, where various (cooperative) relaying schemes have been proposed and analyzed to enhance wireless security

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under different model assumptions and settings. Note that it is possible to improve further the secrecy performance of the considered system by employing jamming/artificial noise schemes at the source, the relay, or the destination to interfere the reception of the eavesdropper [25], [26]. However, such schemes are not considered in this work since depending on transmission protocols, they would generally require multiple-antenna techniques and/or full-duplex capability and/or more power consumption and/or higher processing complexity.

In this paper, we aim to support secure Alice–Bob communication over fading channels in the presence of a passive Eve. In general, we can decide to choose either a dual-hop Alice–Ray–Bob relaying communication or a direct Alice–Bob communication, depending upon Ray's deployment (location, delay-unconstrained/constrained communication etc.), resource allocation schemes, power consumption, and secrecy requirements etc. To help in making suitable decisions, we study buffer-aided adaptive relaying, where the secrecy constraint is imposed in terms of maximum allowable SOP [10], [11]. Alice or Ray can be adaptively scheduled to make a transmission depending upon the instantaneous main channel conditions [27], [28]. It is assumed that Eve can eavesdrop both Alice's and Ray's transmissions (e.g., Eve is located in the communication range of both Alice and Ray) [20], [21]. While there are many existing works on relay-aided secure communication as mentioned previously, [29]–[32] are most relevant to our current work. More specifically, while [29] studied buffer-aided adaptive hybrid half-duplex (HD) and full-duplex (FD) relaying, [30] explored buffer-aided adaptive HD relaying with a wireless-powered relay. Both [29] and [30] assume that the buffer length is finite, and the instantaneous CSI of both the main and eavesdropper channels is known at the legitimate transmitters Alice, and Ray. In contrast, our current work considers infinite buffer length (with or without average delay constraint) [27] and assumes unknown instantaneous CSI of the eavesdropper channels at the legitimate transmitters. Consequently, the problem formulations and mathematical approaches are drastically different in our work and in [29] and [30]. Also, it should be noted that both [29] and [30] and our current work assume randomize-and-forward (RF) HD relaying so that Eve cannot exploit signal combining techniques [21]. Moreover, under similar system model assumptions and design objectives to our work, [31] and [32] developed and optimized various heuristic adaptive relaying schemes without delay constraint consideration. Note that [31] assumes that Eve eavesdrops Ray's transmission only. On the other hand, in our paper, optimal relaying schemes are developed directly for both *delay-unconstrained* and *delay-constrained* communication scenarios, under fixed and adaptive Alice and Ray power allocations. To this end, our main contributions in this paper can be summarized as follows.

1) We derive the throughput–optimal adaptive link scheduling (ALS) solution, which takes into account the fading distributions (of the main and eavesdropper channels), as well as the secrecy constraint. In each frame, either Alice or Ray can be scheduled for data transmission depending on the instantaneous main channel conditions. When the channel conditions are below certain thresholds, no transmission occurs in order to prevent secrecy outage. Further, using the proposed solution approach, we revisit the special case when Eve monitors Ray–Bob transmission only (see [31] with a suboptimal ALS solution), and obtain the optimal solution.

2) To enhance the security performance, our study is extended to the problem of joint ALS and power allocation under maximum (average) power constraint. Alice's and Ray's transmit powers are adaptively allocated depending on the instantaneous main channel conditions. The solutions are derived using Lagrangian approach and convex optimization techniques. It is shown that as the main channel conditions become more favorable, more power is allocated to increase the secrecy rate. Hence, the scheme efficiently exploits both link fading and temporal fading diversities.

3) While focusing solely on throughput maximization, the aforementioned transmission schemes can result in unboundedly large (queuing) delay at Ray's buffer. We next explore transmission schemes guaranteeing bounded average delay [33], [34]. We show that the optimal throughput–delay trade-off is concave increasing. In order to develop transmission schemes achieving the optimal trade-off, we formulate the problem as an infinite horizon average reward constrained Markov decision process (MDP). In addition to the instantaneous channel conditions, our proposed solution takes into account the buffer state to balance the trade-off between throughput maximization and delay minimization. Interestingly, by incorporating the random relay buffer state which is known only at the relay into the transmission control decisions, the buffer-aided secure relaying model under consideration resembles a state-dependent relay channel model (with an external eavesdropper) studied in [35]–[38]. Moreover, it is shown that Alice and Ray can transmit over non-overlapping time fractions of a frame, unlike the unconstrained delay case where it is optimal for either Alice or Ray to transmit in each frame. Toward this end, we develop a transmission algorithm, which does not require a prior statistical information of the main channels and is able to converge to the optimal solution with a faster speed and reduced complexity, compared to conventional reinforcement Q-learning algorithms [39]. This is because the developed algorithm updates or learns a single-dimensional state value function of the buffer state while Q-learning algorithms learn state–action value function with much larger number of states.

4) We numerically compare the throughputs of the ALS scheme and other benchmark transmission schemes under different signal-to-noise power ratio (SNR), and secrecy constraint regimes: 1) Fixed link scheduling (FLS); 2) Non-buffer relaying; 3) Direct Alice–Bob communication. It is shown that the ALS scheme outperforms other relaying schemes. Compared with direct transmission scheme, the ALS scheme performs better when Ray is deployed mid-way between Alice and Bob to improve both main Alice–Ray and Ray–Bob channels. This implies that without appropriate Ray deployment and resource allocation, relaying communication can be inefficient. Moreover, the ALS scheme with adaptive power allocation can provide larger capacity gains over fixed power allocation at lower SNR than at higher SNR regimes,

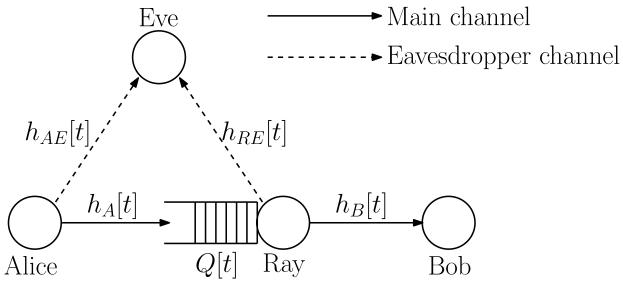


Fig. 1. Buffer-aided secure relaying communication system model.

where the performances are almost unaffected. It implies that adaptive power allocation is more useful to support secure communication at low rates than at high rates. For delay-constrained communication, the developed transmission algorithm can attain higher throughput (for given average delay) and smaller delay (for given throughput) than the algorithm developed without considering the buffer state for transmission scheduling. Also, the algorithm can guarantee any pre-set average delay even when the statistics of the main fading channels are unknown.

The rest of the paper is organized as follows. In Section II, we present the communication system model. In Section III, the throughput–optimal ALS problem is formulated, and the corresponding optimal solution is derived. The joint ALS and power allocation problem is considered in Section IV. In Section V, we explore the transmission schemes considering average delay constraint. Illustrative results are presented in Section VI. Finally, Section VII concludes this work. The lengthy proofs are relegated to the end of the manuscript.

II. System Model

We consider a buffer-aided half-duplex relaying communication network depicted in Fig. 1 where Alice (A) communicates with Bob (B) via Ray (R) using the same frequency with bandwidth B (Hz). Ray buffers the received (and decoded) data from Alice before re-encoding and forwarding the buffered data to Bob in the future using randomize-and-forward (RF) relaying scheme [21], [29]. Moreover, there is a passive Eve (E) eavesdropping both Alice's and Ray's transmissions [21], [29], [30], [32]. Due to RF relaying, Eve cannot exploit combining techniques to jointly process eavesdropped signals from Alice's and Ray's transmissions [21], [29], [30].

A. Channel Model and Assumptions

We assume quasi-static block-fading channels where the channel coefficients remain constant through a transmission block (codeword) of duration T (seconds), and vary independently from one block (or frame) to another. This assumption allows secure communication with a (fixed or varying) target secrecy rate for given secrecy outage probability under unknown CSI of the eavesdropper channels at the legitimate transmitters [10], [11], [13], [31], [32] etc. as will be discussed in more details in the following. Let $h_A[t]$, $h_{AE}[t]$, $h_B[t]$, and $h_{RE}[t], t = 1, 2, \ldots$, denote the (normalized) channel power gains in frame t of the Alice–Ray (A–R), Alice–Eve (A–E), Ray–Bob (R–B), and Ray–Eve (R–E) channels, respectively. Moreover, $h_i[t], i \in \{A, AE, B, RE\}$ are assumed to be independent variables with means $\bar{h}_i$. Let us denote the corresponding cumulative distribution functions (cdf) of the random channel power gains as $F_{h_i}(h_i)$.

Let P_A and P_R denote the (fixed) transmit powers of Alice and Ray, respectively. Without loss of generality (w.l.o.g.), we assume equal $P_A = P_R = P$. Thus, $Ph_i[t], i \in \{A, AE, B, RE\}$ is the link instantaneous SNR in frame t, which is assumed to be available at the corresponding receiver. It is also assumed that Alice knows $h_A[t]$ and Ray knows $h_B[t]$ to adaptively vary the secrecy rates (i.e., adaptive encoding [11]). Furthermore, it is assumed that Alice and Ray do not know $h_{AE}[t]$, and $h_{RE}[t]$, respectively (e.g., passive Eve). Such CSI availability assumption has been considered in many existing works on physical-layer security [10], [11], [13], [31], [32] etc.

B. Adaptive Link Scheduling (ALS)

In an arbitrary frame t, we let $\phi_A[t], \phi_B[t] \in \{0, 1\}, t = 1, 2, \ldots$, denote binary link scheduling variables where we set $\phi_A[t] = 1$ if Alice transmits (e.g., A–R link is scheduled) and otherwise, $\phi_A[t] = 0$. Similarly, $\phi_B[t] = 1$ if Ray transmits (e.g., R–B link is scheduled) and otherwise $\phi_B[t] = 0$. Since at most one of Alice or Ray is allowed to transmit in each frame due to half-duplex relaying constraint (i.e., Ray cannot transmit and receive simultaneously), we require:

$$\phi_A[t] + \phi_B[t] \le 1, \quad \forall t.$$

Note that when $\phi_A[t] = \phi_B[t] = 0$, then neither Alice nor Ray transmits in frame t.

Remark 1: In general, Alice and Ray can also transmit over non-overlapping time fractions of each frame, i.e., time-sharing. However, we can show that throughput–optimal time-sharing transmission scheme will eventually prescribe at most one of Alice or Ray to be transmitting in each frame. We omit the details here for brevity. Hence, by *a-priori* imposing that at most one of Alice or Ray is transmitting in each frame, no performance loss is sacrificed. However, we should emphasize that in Section V where delay-constrained communications is considered, time-sharing solutions are indeed optimal.

Furthermore, if $\phi_A[t] = 1$, then Alice transmits data to Ray with target secrecy rate $r_{AS}[t] > 0$ (b/s/Hz) [11]; otherwise $r_{AS}[t] = 0$. Note that the case of fixed target secrecy rate can also be considered (as in [31], [32]), and we will re-visit this case in Section III.E. We assume that Alice always has data to transmit. When $\phi_A[t] = 1$ (and $r_{AS}[t] > 0$), since Alice does not know the instantaneous CSI of the eavesdropper channel $h_{AE}[t]$, perfect secrecy cannot be achieved, and the following secrecy constraint is imposed to control the risk of secrecy outage for Alice's transmission [10], [11], [13], [31], [32]:

$$\mathrm{Prob}\big(r_{AE}[t] > r_A[t] - r_{AS}[t]\big) \le \zeta_{\mathrm{sop}}, \qquad r_i[t] = \log_2(1 + Ph_i[t]) \quad (1)$$

for $i \in \{A, AE\}$ where $\mathrm{Prob}(A)$ denotes the probability of event A, $\zeta_{\mathrm{sop}} \in (0, 1)$ is the maximum allowable SOP. A smaller ζ_{sop} implies more stringent secrecy constraint, e.g., smaller risk of being outage. Note that when the condition (1) is satisfied, Ray can decode the messages from Alice correctly since it is required that $r_{AS}[t] < r_A[t]$. If $\phi_B[t] = 1$, then Ray transmits its currently buffered data to Bob with secrecy rate $r_{RS}[t] > 0$ (b/s/Hz); otherwise, $r_{RS}[t] = 0$. Similarly, when $\phi_B[t] = 1$ (and $r_{RS}[t] > 0$), the following secrecy constraint is imposed:

$$\text{Prob}\big(r_{RE}[t] > r_B[t] - r_{RS}[t]\big) \leq \zeta_{\text{sop}}, \\ r_i[t] = \log_2(1 + Ph_i[t]) \quad (2)$$

for $i \in \{B, RE\}$.

Remark 2: We should emphasize that randomize-and-forward (RF) HD relaying has been (implicitly) considered in our model, where different codebooks have been used by Alice and Ray (to transmit independent signals) [21], [29], [30]. Hence, even Eve can eavesdrop both Alice's and Ray's transmissions, Eve cannot exploit combining techniques to jointly process eavesdropped signals from Alice's and Ray's transmissions. Hence, it is reasonable to assume that Eve can only process the individual message eavesdropped in each frame (either from Alice or Ray), which leads to the use of expressions (1), and (2) for the target secrecy rates of Alice and Ray.

We can transform the secrecy constraint (1) into a more tractable form as follows.

$$\begin{aligned} &\text{Prob}\big(r_{AE}[t] > r_A[t] - r_{AS}[t]\big) \leq \zeta_{\text{sop}} \\ &\iff \text{Prob}\big(r_{AE}[t] \leq r_A[t] - r_{AS}[t]\big) \geq 1 - \zeta_{\text{sop}} \\ &\iff \text{Prob}\left(h_{AE}[t] \leq \frac{2^{r_A[t] - r_{AS}[t]} - 1}{P}\right) \geq 1 - \zeta_{\text{sop}} \\ &\iff \frac{2^{r_A[t] - r_{AS}[t]} - 1}{P} \geq F^{-1}_{h_{AE}}(1 - \zeta_{\text{sop}}) \\ &\iff r_{AS}[t] \leq r_A[t] - r_A^{\min} \end{aligned}$$

where $F^{-1}_{h_{AE}}(\cdot)$ denotes the inverse function of the cdf $F_{h_{AE}}(h_{AE})$ of h_{AE}, (i.e., $F^{-1}_{h_{AE}}(F_{h_{AE}}(h_{AE})) = h_{AE}$), and

$$r_A^{\min} = \log_2(1 + Ph_A^{\min}), \quad h_A^{\min} = F^{-1}_{h_{AE}}(1 - \zeta_{\text{sop}}).$$

Hence, the constraint (1) can be equivalently expressed as the following two conditions:

$$0 < r_{AS}[t] \leq r_A[t] - r_A^{\min}, \quad r_A[t] > r_A^{\min}. \quad (3)$$

Similarly, the constraint (2) can be written as:

$$0 < r_{RS}[t] \leq r_B[t] - r_B^{\min}, \quad r_B[t] > r_B^{\min} \quad (4)$$

and

$$r_B^{\min} = \log_2(1 + Ph_B^{\min}), \quad h_B^{\min} = F^{-1}_{h_{RE}}(1 - \zeta_{\text{sop}})$$

where $F^{-1}_{h_{RE}}$ is the inverse function of $F_{h_{RE}}$.

C. Secrecy Throughput

Denote $Q[t] \geq 0$ as the queue length of the Ray buffer in frame $t = 1, 2, \ldots$. Then, the queue length evolution is given as:

$$Q[t+1] = Q[t] - \min\big\{Q[t], \phi_B[t]TBr_{RS}[t]\big\} \\ + \phi_A[t]TBr_{AS}[t], \quad t \geq 1. \quad (5)$$

The second term on the right side of (5) is the actual data arriving at Bob in frame t (i.e, the throughput). In the following, for simplifying notation purpose, we let $TB = 1$ w.l.o.g. The (secrecy) throughput is defined as:

$$\begin{aligned} \tau &= \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \min\big\{Q[t], \phi_B[t]r_{RS}[t]\big\} \\ &= \mathbb{E}\big[\min\big\{Q[t], \phi_B[t]r_{RS}[t]\big\}\big] \end{aligned} \quad (6)$$

where $\mathbb{E}[\cdot]$ denotes the statistical expectation operator. In (6), the second equality holds due to ergodic and stationary random channel processes. Analogously, the average arrival rate to Ray buffer is:

$$\lambda = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \phi_A[t]r_{AS}[t] = \mathbb{E}\big[\phi_A[t]r_{AS}[t]\big].$$

Due to flow conservation rule, it is true that: $\lambda \geq \tau$. The average service rate is defined as:

$$\mu = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \phi_B[t]r_{RS}[t] = \mathbb{E}\big[\phi_B[t]r_{RS}[t]\big].$$

Before we proceed, we shall make the following remarks.

Remark 3: It is true that $\tau = \min\{\lambda, \mu\}$. Hence, in order to maximize τ, in frame t, when $\phi_A[t] = 1$ (or $\phi_B[t] = 1$), it is optimal for Alice (or Ray, respectively) to transmit with secrecy rate $r_{AS}[t] = r_A[t] - r_A^{\min} > 0$ (or $r_{RS}[t] = r_B[t] - r_A^{\min} > 0$, respectively) to maximize λ (or μ, respectively).

Remark 4: It should be noted that in our model, the data buffer is assumed to have infinite size, and buffer overflow is not considered. In practice, avoiding buffer overflow can affect the transmission decisions, which in turn can impact the secrecy performance. Studying this relationship is an interesting problem in future works. Note that the works [29] and [30] have considered buffer-aided relaying for secure communication with finite buffer length, where the relaying mode depends on both the channel conditions and buffer state. Alternatively, the relaying schemes in our work (for delay-unconstrained communications) do not depend on the buffer state.

III. Optimal Adaptive Link Scheduling

In this section, we first formulate the throughput–optimal ALS problem, and then present the optimal solution.

A. Problem Formulation

The throughput–optimal ALS problem can be formulated as follows:

$$\max_{\phi_A[t], \phi_B[t], \forall t} \quad \tau \quad (7a)$$

$$\texttt{s.t.:} \; r_i[t] > \phi_i[t]r_i^{\min}, \quad i \in \{A, B\}, \; \forall t, \quad (7b)$$

$$\phi_A[t] + \phi_B[t] \leq 1, \quad \phi_A[t], \phi_B[t] \in \{0, 1\}, \; \forall t. \quad (7c)$$

Denote τ^* the optimal (secrecy) throughput. We now solve the problem (7a)–(7c).

B. Problem Reformulation

Before we proceed, we consider the following transmission schemes.

The first scheme $(\phi_A^\dagger[t], \phi_B^\dagger[t])$ prescribes transmissions in frame t as follows:

$$(\phi_A^\dagger[t], \phi_B^\dagger[t]) = \begin{cases} (1,0), & r_A[t] > r_A^{\min}, \\ (0,1), & r_B[t] > r_B^{\min} \text{ and } r_A[t] \le r_A^{\min}, \\ (0,0), & \text{otherwise.} \end{cases}$$

In this scheme, Alice is transmitting whenever Alice's transmission satisfies the secrecy constraint. If it is true that:

$$\lambda^\dagger = \mathbb{E}[\phi_A^\dagger[t] r_{AS}[t]] \le \mu^\dagger = \mathbb{E}[\phi_B^\dagger[t] r_{RS}[t]] \quad (8)$$

then, $\tau^* = \lambda^\dagger$ and $(\phi_A^\dagger[t], \phi_B^\dagger[t])$ is the optimal solution of (7a)–(7c). This case can happen when the throughput of the R–B channel is much larger than that of the A–R channel.

Consider another scheme $(\phi_A^\ddagger[t], \phi_B^\ddagger[t])$ as follows:

$$(\phi_A^\ddagger[t], \phi_B^\ddagger[t]) = \begin{cases} (1,0), & r_A[t] > r_A^{\min} \text{ and } r_B[t] \le r_B^{\min}, \\ (0,1), & r_B[t] > r_B^{\min}, \\ (0,0), & \text{otherwise.} \end{cases}$$

In this scheme, Ray is transmitting whenever its transmission satisfies the secrecy constraint. If it is true that:

$$\lambda^\ddagger = \mathbb{E}[\phi_A^\ddagger[t] r_{AS}[t]] \ge \mu^\ddagger = \mathbb{E}[\phi_B^\ddagger[t] r_{RS}[t]] \quad (9)$$

then, $\tau^* = \mu^\ddagger$ and $(\phi_A^\ddagger[t], \phi_B^\ddagger[t])$ is optimal.

In the following, we assume neither of the above transmission schemes is optimal, i.e.,

$$\lambda^\dagger > \mu^\dagger, \quad \lambda^\ddagger < \mu^\ddagger. \quad (10)$$

It implies that for the case $r_A[t] > r_A^{\min}$ and $r_B[t] > r_B^{\min}$, both Alice or Ray can be allowed to transmit depending on the actual values of $r_A[t]$, and $r_B[t]$.

Under the above assumption, the optimal transmission scheme must ensure equal average arrival and service rates, which is also the throughput as mentioned in *Remark 3*. Hence, (7a)–(7c) is equivalent to the following problem:

$$\max_{\phi_A[t], \phi_B[t], \forall t} \tau \quad \texttt{s.t.:} \ \tau = \lambda = \mu, \quad \text{Constraints (7b), (7c).} \quad (11)$$

C. Optimal Solution

We now solve (11) for the optimal solution. We can rewrite (11) as:

$$\max_{\phi_A[t], \phi_B[t], \forall t} \mathbb{E}\big[\phi_B[t] r_{RS}[t]\big] \quad (12a)$$

$$\texttt{s.t:} \ \mathbb{E}\big[\phi_A[t] r_{AS}[t]\big] = \mathbb{E}\big[\phi_B[t] r_{RS}[t]\big], \quad (12b)$$

$$\text{Constraints (7b), (7c).} \quad (12c)$$

To solve (12a)–(12c), we employ the Lagrangian approach for constrained optimization. Specifically, by absorbing the rate equality constraint into the Lagrangian function, we have the following Lagrangian maximization problem:

$$\max_{\phi_A[t], \phi_B[t], \forall t} \mathbb{E}\big[(1-\xi)\phi_B[t] r_{RS}[t] + \xi \phi_A[t] r_{AS}[t]\big] \quad \texttt{s.t.:} \ \text{Constraints (7b), (7c)} \quad (13)$$

where ξ is the Lagrange multiplier associated with the equality constraint (12b). Note that $\xi \in (0,1)$ to avoid $\phi_B[t] = 0, \forall t$, which is clearly not optimal.

Now if we can solve (13) for the optimal solution $\phi_A^*[t]$, and $\phi_B^*[t], \forall t$, and the multiplier ξ is determined so that the equality constraint is satisfied:

$$\mathbb{E}\big[\phi_A^*[t] r_{AS}[t]\big] = \mathbb{E}\big[\phi_B^*[t] r_{RS}[t]\big] \quad (14)$$

then, from the Lagrangian sufficiency theorem, $\phi_A^*[t]$, and $\phi_B^*[t], \forall t$ is also the optimal solution of (12a)–(12c).

Now, the optimal solution $(\phi_A^*[t], \phi_B^*[t])$ in frame t of (13) is determined as:

$$\max_{\phi_A[t], \phi_B[t], \forall t} (1-\xi)\phi_B[t] r_{RS}[t] + \xi \phi_A[t] r_{AS}[t] \quad \texttt{s.t.:} \ \text{Constraints (7b), (7c).} \quad (15)$$

The solution can be derived using inspection as follows:

$$(\phi_A^*[t], \phi_B^*[t]) = \begin{cases} (1,0), & r_A[t] > r_A^{\min} \text{ and } r_{AS}[t] \ge \dfrac{1-\xi}{\xi} r_{RS}[t], \\ (0,1), & r_B[t] > r_B^{\min} \text{ and } r_{RS}[t] > \dfrac{\xi}{1-\xi} r_{AS}[t], \\ (0,0), & \text{otherwise.} \end{cases}$$

Denote $\chi = (1-\xi)/\xi \in (0, \infty)$. For χ being determined such that (14) is satisfied, we obtain the solution for (12a)–(12c). In the following, we argue that such χ exists and is unique.

The average power of the ALS scheme can be computed as:

$$\mathcal{P}^{\text{ALS}} = P\mathbb{E}[\phi_A^*[t] + \phi_B^*[t]] = P(1 - F_{h_A}(h_A^{\min}) F_{h_B}(h_B^{\min})). \quad (16)$$

D. Computing the Multiplier χ

In the following, we describe the approach to find the unique χ satisfying (14). First, we need to compute the expectations in (14). For notational simplicity and convenience, we define the following functions:

$$r_{AS} \ge \chi r_{RS} \iff h_A \ge g_B(h_B, \chi) \iff h_B \le g_A(h_A, \chi). \quad (17)$$

We have:

$$\mathbb{E}\big[\phi_A^*[t] r_{AS}[t]\big] = F_{h_B}(h_B^{\min}) \times \int_{h_A^{\min}}^{\infty} r_{AS} \, dF_{h_A}(h_A) + \int_{h_B^{\min}}^{\infty} \int_{g_B(h_B,\chi)}^{\infty} r_{AS} \, dF_{h_A}(h_A) \, dF_{h_B}(h_B) \quad (18)$$

and

$$\mathbb{E}\big[\phi_B^*[t] r_{RS}[t]\big] = F_{h_A}(h_A^{\min}) \times \int_{h_B^{\min}}^{\infty} r_{RS} \, dF_{h_B}(h_B) + \int_{h_A^{\min}}^{\infty} \int_{g_A(h_A,\chi)}^{\infty} r_{RS} \, dF_{h_B}(h_B) \, dF_{h_A}(h_A). \quad (19)$$

We can see that the terms in (18) and (19) decreases, and increases, respectively, with increasing $\chi \in (0,\infty)$. Hence, the difference between them $\mathcal{D}(\chi) = \mathbb{E}\big[\phi_A^*[t]r_{AS}[t]\big] - \mathbb{E}\big[\phi_B^*[t]r_{RS}[t]\big]$ decreases with increasing χ. Moreover, we note that:

$$\lim_{\chi\to 0}\mathcal{D}(\chi) = \lambda^\dagger - \mu^\dagger, \quad \lim_{\chi\to\infty}\mathcal{D}(\chi) = \lambda^\ddagger - \mu^\ddagger \tag{20}$$

where the rates are computed as in (8), and (9).

Due to assumption (10), we can see that $\lim_{\chi\to 0}\mathcal{D}(\chi) > 0 > \lim_{\chi\to\infty}\mathcal{D}(\chi)$. Hence, there exists an unique $\chi^* \in (0,\infty)$ such that $\mathcal{D}(\chi^*)$ is equal to 0. Such χ^* can be found using a simple bisection search, which is omitted due to space limitation. Computing expressions (18) and (19) in closed-form for general fading distributions can be challenging and we have to resort to numerical integration. However, for the case of Rayleigh fading channels, we can simplify (18) and (19) as follows.

First, for Rayleigh fading channels, the distribution functions of the channel gains are:

$$F_{h_i}(x) = 1 - e^{-\lambda_i x}, \quad \lambda_i = \frac{1}{\bar{h}_i}, \ i = \{A, AE, B, RE\}.$$

W.l.o.g., assume $P = 1$. We first compute expression (18), which can be expanded as follows:

$$\begin{aligned}
&\mathbb{E}\big[\phi_A^*[t]r_{AS}[t]\big] \\
&= F_{h_B}(h_B^{\min}) \times \int_{h_A^{\min}}^{\infty} \Big[\log_2(1+h_A) - r_A^{\min}\Big] dF_{h_A}(h_A) \\
&\quad + \int_{h_B^{\min}}^{\infty} \int_{g_B(h_B,\chi)}^{\infty} \big[\log_2(1+h_A) - r_A^{\min}\big] dF_{h_A}(h_A) dF_{h_B}(h_B).
\end{aligned}$$

We first have for $x \geq 0$:

$$\int_x^\infty r_A^{\min} dF_{h_A}(h_A) = r_A^{\min} e^{-\lambda_A x}$$

and by using integration by parts:

$$\begin{aligned}
&\int_x^\infty \log_2(1+h_A) dF_{h_A}(h_A) \\
&\quad = \int_x^\infty \log_2(1+h_A)\lambda_A e^{-\lambda_A h_A} dh_A \\
&\quad = \frac{1}{\log(2)}\Big[e^{-\lambda_A x}\log(1+x) + e^{\lambda_A} E_1((1+x)\lambda_A)\Big]
\end{aligned}$$

where $E_1(\cdot)$ is the exponential-integral function. For given χ, the outer integral in (18) can be computed numerically, for example, by using MATLAB. Expression (19) can be computed similarly.

E. Special Case: Eve Eavesdrops Ray's Transmission Only

Some existing works have assumed that Eve eavesdrops Ray–Bob data transmissions only, i.e., Eve is outside of the communication range of Alice [24], [31]. In our model, this case can be modeled as $\bar{h}_{AE} = 0$, and hence, $h_A^{\min} = r_A^{\min} = 0$ and $r_{AS}[t] = r_A[t]$. Omitting the details due to space limitation, the optimal ALS scheme in this case can be obtained as follows. Consider the following transmission scheme:

$$(\phi_A^\perp[t], \phi_B^\perp[t]) = \begin{cases} (0,1), & r_B[t] > r_B^{\min}, \\ (1,0), & \text{otherwise.} \end{cases} \tag{21}$$

Here, Ray is transmitting whenever its transmission satisfies the secrecy constraint. If it is true that $\mathbb{E}[\phi_A^\perp[t]r_A[t]] \geq \mathbb{E}[\phi_B^\perp[t]r_{RS}[t]]$, then $(\phi_A^\perp[t], \phi_B^\perp[t])$ is throughput–optimal. Otherwise, the optimal transmission scheme has the following form:

$$(\phi_A^*[t], \phi_B^*[t]) = \begin{cases} (0,1), & r_B[t] > \chi r_A[t] + r_B^{\min}, \\ (1,0), & \text{otherwise} \end{cases} \tag{22}$$

where $\chi \in (0,\infty)$ is determined such that $\mathbb{E}[\phi_A^*[t]r_A[t]] = \mathbb{E}[\phi_B^*[t]r_{RS}[t]]$.

In [31], it is assumed that when Ray transmits, he transmits with fixed rate r_{RS}. Using our approach, we can derive the optimal transmission scheme in this case as:

$$(\phi_A^*[t], \phi_B^*[t]) = \begin{cases} (0,1), \ r_B[t] > \max\big\{r_{RS} + r_B^{\min}, \\ \qquad\qquad\qquad\qquad \chi r_A[t] + r_B^{\min}\big\}, \\ (1,0), \ \text{otherwise} \end{cases} \tag{23}$$

where $\chi \in (0,\infty)$ is determined such that $\mathbb{E}[\phi_A^*[t]r_A[t]] = \mathbb{E}[\phi_B^*[t]r_{RS}]$. The secrecy rate r_{RS} can also be optimized to achieve largest throughput. Note that (23) corrects the result derived in [31] which is claimed to be optimal.

IV. Adaptive Link Scheduling and Power Allocation

A. Problem Formulation

In the previous section, we have assumed that Alice and Ray have fixed transmit powers P. In this section we consider adaptive power allocation to Alice and Ray in order to exploit the temporal fading diversity for further potential throughput enhancement. More specifically, in frame t, let Alice and Ray transmit powers be denoted as $P_A[t]$ and $P_R[t]$, respectively. If $\phi_A[t] = 1$ then $P_A[t] > 0$ and $P_R[t] = 0$ while if $\phi_B[t] = 1$ then $P_A[t] = 0$ and $P_R[t] > 0$. Then, the average power is given by:

$$\mathbb{E}\big[\phi_A[t]P_A[t] + \phi_B[t]P_R[t]\big]. \tag{24}$$

Note that in order to have $\phi_A[t] = 1$ and $P_A[t] > 0$, a necessary condition is $h_A[t] > h_A^{\min}$. Using similar approach as in the case of fixed power allocation, the maximum secrecy rate for Alice to satisfy the SOP constraint is given by:

$$r_{AS}[t] = \log_2(1 + P_A[t]h_A[t]) - \log_2(1 + P_A[t]h_A^{\min}). \tag{25}$$

Analogously, for $\phi_B[t] = 1$ and $P_R[t] > 0$, we have:

$$r_{RS}[t] = \log_2(1 + P_R[t]h_B[t]) - \log_2(1 + P_R[t]h_B^{\min}) \tag{26}$$

which is feasible for $h_B[t] > h_B^{\min}$ only.

The joint ALS and power allocation problem can be formulated as follows:

$$\max_{\phi_A[t],\phi_B[t],P_A[t],P_R[t],\forall t} \mathbb{E}\big[\phi_B[t]r_{RS}[t]\big] \tag{27a}$$

$$\texttt{s.t.:}\ \mathbb{E}\big[\phi_A[t]r_{AS}[t]\big]=\mathbb{E}\big[\phi_B[t]r_{RS}[t]\big], \tag{27b}$$

$$\mathbb{E}\big[\phi_A[t]P_A[t]+\phi_B[t]P_R[t]\big]\le \mathcal{P}^{\max}, \tag{27c}$$

$$h_i[t]>\phi_i[t]h_i^{\min},\quad i\in\{A,B\},\ \forall t, \tag{27d}$$

$$\phi_A[t]+\phi_B[t]\le 1,\quad \phi_A[t],\phi_B[t]\in\{0,1\},\ \forall t, \tag{27e}$$

$$P_A[t],\quad P_R[t]\ge 0,\ \forall t \tag{27f}$$

where $\mathcal{P}^{\max}$ is the maximum average power. By setting $\mathcal{P}^{\max}$ equal to $\mathcal{P}^{\rm ALS}$ in (16), we can ensure that the ALS schemes with fixed and adaptive power allocation consume similar average power (for fair throughput comparisons).

B. Optimal Solution

Similar to the fixed power allocation case, we use Lagrangian approach. The Lagrangian maximization problem of (27a)–(27f) is written as:

$$\max_{\phi_A[t],\phi_B[t],P_A[t],P_R[t],\forall t} \mathbb{E}\Big[(1-\omega)\phi_B[t]r_{RS}[t]+\omega\phi_A[t]r_{AS}[t] -\sigma\big(\phi_A[t]P_A[t]+\phi_B[t]P_R[t]\big)\Big]$$
$$\texttt{s.t.:}\ \text{Constraints (27d), (27e), (27f)} \tag{28}$$

where ω, and $\sigma>0$ are the Lagrange multipliers associated with the rate equality and power inequality constraints in (27b) and (27c), respectively. Again, we can see that $\omega\in(0,1)$ to avoid $\phi_B[t]=0,\forall t$.

We first study the adaptive power allocation solution assuming the link scheduling solution is given. First, by assuming $h_A[t]>h_A^{\min}$ and considering $\phi_A[t]=1$, we have the power allocation problem in frame t for Alice as follows:

$$\arg\max_{P_A[t]\ge 0}\ \omega\Big(\log_2(1+P_A[t]h_A[t])-\log_2(1+P_A[t]h_A^{\min})\Big) -\sigma P_A[t]. \tag{29}$$

We can compute the second derivative of the objective function in (29) with $P_A[t]$ as:

$$\frac{\omega}{\log(2)}\frac{(h_A^{\min})^2-h_A^2[t]+2h_A^{\min}h_A[t]P_A[t](h_A^{\min}-h_A[t])}{(1+P_A[t]h_A[t])^2(1+P_A[t]h_A^{\min})^2}$$

which is strictly negative for $h_A^{\min}<h_A[t]$. Hence, (29) is a convex optimization problem due to the concavity of the objective function. We can derive the optimal power allocation for Alice as:

$$P_A^*[t]=\begin{cases}\frac{1}{2}\Bigg[\sqrt{\Big(\frac{1}{h_A^{\min}}-\frac{1}{h_A[t]}\Big)^2+\frac{4\omega}{\sigma\log(2)}\Big(\frac{1}{h_A^{\min}}-\frac{1}{h_A[t]}\Big)} -\Big(\frac{1}{h_A^{\min}}+\frac{1}{h_A[t]}\Big)\Bigg], & h_A[t]-h_A^{\min}>\frac{\sigma\log(2)}{\omega},\\ 0, & \text{otherwise.}\end{cases} \tag{30}$$

The secrecy rate allocation for Alice is thus:

$$r_{AS}^*[t]=\log_2(1+P_A^*[t]h_A[t])-\log_2(1+P_A^*[t]h_A^{\min}). \tag{31}$$

Similarly, assume $h_B[t]>h_B^{\min}$ and consider $\phi_B[t]=1$, we derive the optimal power and secrecy rate allocation for Ray as follows:

$$P_R^*[t]=\begin{cases}\frac{1}{2}\Bigg[\sqrt{\Big(\frac{1}{h_B^{\min}}-\frac{1}{h_B[t]}\Big)^2+\frac{4(1-\omega)}{\sigma\log(2)}\Big(\frac{1}{h_B^{\min}}-\frac{1}{h_B[t]}\Big)} -\Big(\frac{1}{h_B^{\min}}+\frac{1}{h_B[t]}\Big)\Bigg], & h_B[t]-h_B^{\min}>\frac{\sigma\log(2)}{1-\omega},\\ 0, & \text{otherwise}\end{cases} \tag{32}$$

and

$$r_{RS}^*[t]=\log_2(1+P_R^*[t]h_B[t])-\log_2(1+P_R^*[t]h_B^{\min}). \tag{33}$$

We can derive the optimal ALS solution to maximize the Lagrangian (28) in frame t considering the following cases:

- *Case 1:* $h_A[t]\le h_A^{\min}+\frac{\sigma\log(2)}{\omega}$ and $h_B[t]\le h_B^{\min}+\frac{\sigma\log(2)}{1-\omega}$: $(\phi_A^*[t],\phi_B^*[t])=(0,0)$.
- *Case 2:* $h_A[t]> h_A^{\min}+\frac{\sigma\log(2)}{\omega}$ and $h_B[t]\le h_B^{\min}+\frac{\sigma\log(2)}{1-\omega}$: $(\phi_A^*[t],\phi_B^*[t])=(1,0)$.
- *Case 3:* $h_A[t]\le h_A^{\min}+\frac{\sigma\log(2)}{\omega}$ and $h_B[t]> h_B^{\min}+\frac{\sigma\log(2)}{1-\omega}$: $(\phi_A^*[t],\phi_B^*[t])=(0,1)$.
- *Case 4:* $h_A[t]> h_A^{\min}+\frac{\sigma\log(2)}{\omega}$ and $h_B[t]> h_B^{\min}+\frac{\sigma\log(2)}{1-\omega}$. The solution is determined as:

$$(\phi_A^*[t],\phi_B^*[t])=\begin{cases}(1,0), & \omega r_{AS}^*[t]-\sigma P_A^*[t]\ge (1-\omega)r_{RS}^*[t]-\sigma P_R^*[t],\\ (0,1), & \text{otherwise.}\end{cases}$$

The multipliers $\omega\in(0,1)$ and $\sigma>0$ satisfy:

$$\mathbb{E}\big[\phi_A^*[t]r_{AS}^*[t]\big]=\mathbb{E}\big[\phi_B^*[t]r_{RS}^*[t]\big]$$

and

$$\mathbb{E}\big[\phi_A^*[t]P_A^*[t]+\phi_B^*[t]P_R^*[t]\big]=\mathcal{P}^{\max}. \tag{34}$$

Remark 5: It can be easily shown that the objective function of (29) is supermodular in $(P_A[t],h_A[t])$. Hence, due to Topkis's Theorem, $P_A^*[t]$ (and hence, $r_{AS}^*[t]$) increases with increasing $h_A[t]$. Similarly, $P_R^*[t]$, and $r_{RS}^*[t]$ also increase with increasing $h_B[t]$. It implies that more power is allocated under more favorable main channel conditions to increase the secrecy rates.

C. Iterative Transmission Algorithm Over Unknown Fading Statistics

The joint ALS and power allocation solution depends on the fading statistics of the main channels through the Lagrange multipliers ω and σ, which satisfy (34). We can use a (two-dimension) numerical search method as in the case of fixed power allocation. However, such numerical approach has two possible limitations: 1) It requires the fading statistics to be known, which is usually not the case in reality; 2) Even when the fading statistics are known, it may be complicated, if not impossible, to compute the expectation terms in (34). Hence, numerical methods to compute the Lagrange multipliers might not be desirable. To overcome these limitations, we can utilize the following iterative allocation algorithm. We initialize $\omega[1] \in (0,1)$, and $\sigma[1] > 0$. Then, in frame $t = 1, 2, \ldots$, we carry out the following updates:

$$\omega[t+1] = \Big[\omega[t] - \varsigma[t]\Big(\phi_A^*[t]r_{AS}^*[t] - \phi_B^*[t]r_{RS}^*[t]\Big)\Big]_{\varepsilon}^{1-\varepsilon}$$
$$\sigma[t+1] = \Big[\sigma[t] - \varsigma[t]\Big(\mathcal{P}^{\max} - \phi_A^*[t]P_A^*[t] - \phi_B^*[t]P_R^*[t]\Big)\Big]_0^L$$

for small $\varepsilon > 0$ and large $L > 0$ where $[x]_a^b$ denotes the projection of x on the interval $[a, b]$ for $a \le b$. The decreasing positive sequence $\varsigma[t]$ that dictates the convergence speed, satisfies:

$$\sum_{t=1}^{\infty} \varsigma[t] = \infty; \quad \sum_{t=1}^{\infty} (\varsigma[t])^2 < \infty.$$

The optimal allocation solutions in frame t are computed from convex optimization problems as described in Section IV.B using the current multiplier estimates $\omega[t]$ and $\sigma[t]$. Hence, these iterative stochastic-approximation updates are guaranteed to converge to the optimal multipliers satisfying (34). We can see that these updates do not require the statistical information of the fading channels and have very low implementation complexity. Moreover, the algorithm does not assume any specification on the fading statistics, and it converges for any independent fading distributions. Hence, it is very robust to channel model variations.

V. Communication Under Average Delay Constraint

In previous sections, we have focused on throughput maximization without considering (queueing) delay incurred at the Ray buffer. In fact, the induced delay can be unbounded when the average arrival rate is equal to or larger than the average service rate. This section explores transmission schemes for delay-constrained communication where the average delay is upper-bounded. For simplicity, we only consider the case of fixed power allocation.

A. Problem Formulation

Consider the stable Ray queue with finite average queue length.[1] For optimal secrecy throughput under delay constraint, we consider time-sharing transmission schemes as mentioned in *Remark 1*. In particular, in frame t, if $r_A[t] > r_A^{\min}$, Alice will transmit with secrecy rate $r_{AS}[t] = r_A[t] - r_A^{\min}$ during a fraction $\phi_A[t] \in [0, 1]$ of the frame duration; otherwise, $\phi_A[t] = 0$. Similarly, if $r_B[t] > r_B^{\min}$, Ray will transmit with secrecy rate $r_{RS}[t] = r_B[t] - r_B^{\min}$ during a fraction $\phi_B[t] \in [0, 1]$ of the frame duration; otherwise, $\phi_B[t] = 0$. Clearly, we require that $\phi_A[t] + \phi_B[t] \in [0, 1], \forall t$. The queue state dynamics can be written as:

$$Q[t+1] = Q[t] + \phi_A[t]r_{AS}[t] - \min\big\{Q[t] + \phi_A[t]r_{AS}[t], \phi_B[t]r_{RS}[t]\big\}. \quad (35)$$

Note that data arrivals in frame t can also be transmitted in the same frame to improve the throughput and reduce the delay at the same time. In this case, the throughput is equal to the average arrival rate as mentioned in *Remark 3*.

The stochastic throughput–optimal transmission problem under average queue length (or equivalently, delay) constraint is cast as:

$$\max_{\phi_A[t],\phi_B[t],\forall t} \quad \mathbb{E}[\phi_A[t]r_{AS}[t]] \quad (36a)$$
$$\texttt{s.t.:}\ \mathbb{E}[Q[t]] \le \bar{Q}^{\max} \quad (36b)$$
$$r_i[t] > \lceil \phi_i[t] \rceil\, r_i^{\min}, \quad i \in \{A, B\}, \forall t, \quad (36c)$$
$$\phi_A[t] + \phi_B[t] \le 1, \quad \phi_A[t],\ \phi_B[t] \in [0,1],\ \forall t \quad (36d)$$

where $\bar{Q}^{\max}$ is the maximum (finite) average queue length and $\lceil\cdot\rceil$ denotes the ceiling operator. When $\bar{Q}^{\max}$ becomes very large (but finite), the average queue length constraint approaches the following constraint:

$$\mathbb{E}[\phi_A[t]r_{AS}[t]] = \mathbb{E}[\phi_B[t]r_{RS}[t]].$$

Hence, the resulting optimization problem can be shown to be equivalent to problem (12a)–(12c).

B. Optimal Throughput–Delay Trade-Off

Denote $\tau^*(\bar{Q})$ the optimal throughout of (36a)–(36d) when $\bar{Q}^{\max}$ is equal to $\bar{Q}$. We next characterize the optimal throughput–delay trade-off.

Theorem 1: $\tau^*(\bar{Q})$ is concave increasing with increasing $\bar{Q}$. Moreover, $\lim_{\bar{Q}\to\infty} \tau^*(\bar{Q}) = \tau^*$, the optimal value of (7a)–(7c).

Proof: The proof is presented in Appendix A. ■

In the following, we develop transmission schemes to achieve such optimal trade-off.

C. Optimal Solution

We can see that (36a)–(36d) is an infinite horizon average reward constrained Markov decision process (MDP). Using Lagrangian approach, (36a)–(36d) can be solved as follows [42]:

$$\max_{\beta>0} \left[\max_{\phi_A[t],\phi_B[t],\forall t} \mathbb{E}\big[\phi_A[t]r_{AS}[t] - \beta Q[t]\big] + \beta\bar{Q}^{\max}\right]$$
$$\texttt{s.t.:}\ \text{Constraints (36c), (36d)} \quad (37)$$

where $\beta > 0$ is the Lagrange multiplier associated with the queue length inequality constraint.

Consider the inner maximization problem for a fixed $\beta > 0$, which is an unconstrained MDP. The optimal solution satisfies

[1]Note that the transmission scheme developed in this section ensures that the average queue length is smaller or equal to a (finite) maximum value. Hence, the stability assumption of the data queue is not affected.

the following Bellman equation:

$$\begin{aligned} &v^* + v(Q; h_A, h_B) \\ &= \max_{\phi_A,\phi_B} \phi_A r_{AS} - \beta Q + \int_{\tilde{h}_A,\tilde{h}_B} v(Q + \phi_A r_{AS} \\ &\quad - \min\{Q+\phi_A r_{AS}, \phi_B r_{RS}\}; \tilde{h}_A, \tilde{h}_B) dF_{h_A}(\tilde{h}_A) dF_{h_B}(\tilde{h}_B) \\ &\quad \texttt{s.t.:}\ r_i > \lceil \phi_i \rceil r_i^{\min}, \quad i \in \{A, B\}, \\ &\qquad \phi_A + \phi_B \le 1, \quad \phi_A,\ \phi_B \in [0,1] \end{aligned} \tag{38}$$

for the state value function $v(Q; h_A, h_B)$ and v^* is the optimal value of the unconstrained MDP.

Solving the equation (38) is challenging since the expectation operator is inside the maximization operation. To overcome this difficulty, we define a new single-dimension state value function as follows:

$$\bar{v}(Q) = \int_{\tilde{h}_A,\tilde{h}_B} v(Q; \tilde{h}_A, \tilde{h}_B) dF_{h_A}(\tilde{h}_A) dF_{h_B}(\tilde{h}_B). \tag{39}$$

Then, by using $\bar{v}(Q)$, we can re-write the Bellman equation (38) as:

$$\begin{aligned} v^* + v(Q; h_A, h_B) = \max_{\phi_A,\phi_B} &\phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} \\ &- \min\{Q + \phi_A r_{AS}, \phi_B r_{RS}\}). \end{aligned} \tag{40}$$

Note that we have omitted the constraints in (38) for simplicity. From (39) and (40), we can write the recursion relationship for $\bar{v}(Q)$ as:

$$\begin{aligned} v^* + \bar{v}(Q) = \int_{h_A,h_B} \Big[&\max_{\phi_A,\phi_B} \phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} \\ &- \min\{Q + \phi_A r_{AS}, \phi_B r_{RS}\}) \Big] dF_{h_A}(h_A) dF_{h_B}(h_B). \end{aligned} \tag{41}$$

We can see that the expectation operator has been moved outside of the maximization operator. Such structure allows us to learn the function $\bar{v}(Q)$ using stochastic approximation as explained in the following.

The following lemma characterizes the property of $\bar{v}(Q)$.

Lemma 1: $\bar{v}(Q)$ is concave decreasing with Q.

Proof: The proof is presented in Appendix B. ■

Now in frame t, depending on the channel conditions $h_A[t]$, and $h_B[t]$, and the queue state $Q[t]$, the transmission solution can be found as follows:

$$\begin{aligned} (\phi_A^*[t], \phi_B^*[t]) = \arg\max_{\phi_A[t],\phi_B[t]} &\phi_A[t] r_{AS}[t] + \bar{v}(Q[t] \\ &+ \phi_A[t] r_{AS}[t] - \phi_B[t] r_{RS}[t]) \\ &\texttt{s.t.:}\ \text{Constraints (36c), (36d).} \end{aligned} \tag{42}$$

Problem (42) does not involve expectation operators. Moreover, it is a concave maximization problem due to Lemma 1, which can be solved efficiently.

Remark 6: From (42) and Lemma 1, using supermodular and submodular properties and Topkis's Theorem, in frame t, we can see that $\phi_A^*[t]$, and $\phi_B^*[t]$ are decreasing, and increasing with $Q[t]$. It implies that when the buffer state becomes larger, less data should be entered into and more data should be removed from the buffer to avoid delay constraint violation.

Computing the Value Function $\bar{v}(Q)$: We have seen that in order to compute the transmission solution in frame t using (42), we need to know the value function $\bar{v}(Q)$, which needs to satisfy the recursion relationship (41). In principle, to compute $\bar{v}(Q)$, we can use MDP algorithms such as value iteration algorithm or linear programming reformulation approach etc. In the following, we rely on the relative value iteration algorithm (RVIA) to compute $\bar{v}(Q)$. The RVIA to compute $\bar{v}(Q)$ is written as:

$$\begin{aligned} \bar{v}(Q)[t+1] = \int_{h_A,h_B} \max_{\phi_A,\phi_B} &\phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} \\ &- \min\{Q + \phi_A r_{AS}, \phi_B r_{RS}\})[t] - \bar{v}(Q_0)[t] \end{aligned} \tag{43}$$

for $t = 1, 2, \ldots$ with some initial $\bar{v}(Q)[1]$, where Q_0 is some arbitrary but fixed buffer state. As $t \to \infty$, $\bar{v}(Q)[t+1]$ converges to $\bar{v}(Q)$ satisfying (41) [34]. Note that in (43), we have subtracted $\bar{v}(Q_0)[t]$ to keep the iterations stable.

D. Online Transmission Algorithm for Delay-Constrained Communications

We have seen that it can be non-trivial to compute $\bar{v}(Q)$ using RVIA equation (43), even when the fading statistics is available. Toward this end, we develop the following online transmission algorithm to iteratively learn $\bar{v}(Q)$ over frames using realizations from the random fading processes, which does not require a-priori known fading statistics. The online **Algorithm 1** can be described as follows. First, we initialize the value function $\bar{v}(Q)[1]$ to some concave decreasing function, (e.g., linear function), multiplier $\beta[1] > 0$, queue state $Q[1]$. Also, fix some (arbitrary) queue state Q_0. Then, in each frame $t = 1, 2, \ldots$, after observing the channel conditions $h_A[t]$, $h_B[t]$, and the current queue state $Q[t]$, we compute the transmission solution $\phi_A^*[t]$ and $\phi_B^*[t]$ using the current estimates of the value function $\bar{v}(Q)[t]$ and multiplier $\beta[t]$. Last, we update $\bar{v}(Q)[t+1]$, $\beta[t+1]$, and $Q[t+1]$ accordingly. The details of the operations are described in the following.

Algorithm 1 Online Transmission Algorithm for Delay-Constrained Communications

Initialize value function $\bar{v}(Q)[1]$, multiplier $\beta[1] > 0$, and queue state $Q[1] > 0$.
for $t = 1, 2, \ldots$ **do**
  1) Transmission phase:
  - Observe current queue state $Q[t]$, channel conditions $h_A[t]$, and $h_B[t]$.
  - Compute $\phi_A^*[t]$, and $\phi_B^*[t]$ using $\bar{v}(Q)[t]$, and $\beta[t]$.
  2) Updating phase:
  - Update $\bar{v}(Q)[t+1]$, $\beta[t+1] > 0$, and $Q[t+1]$.
end

- *Initialization phase:* We initialize value function $\bar{v}(Q)[1]$, multiplier $\beta[1] \ge 0$, and queue state $Q[1] \ge 0$.
- *Transmission phase:* In frame $t = 1, 2, \cdots$, from the queue state $Q[t]$, and channel gains $h_A[t]$, and $h_B[t]$,

we determine the transmission solution by considering the following cases.

- *Case 1:* $r_A[t] \leq r_A^{\min}$ and $r_B[t] \leq r_B^{\min}$: $\phi_A^*[t] = \phi_B^*[t] = 0$.
- *Case 2:* $r_A[t] > r_A^{\min}$ and $r_B[t] \leq r_B^{\min}$: $\phi_B^*[t] = 0$, and

$$\phi_A^*[t] = \arg\max_{\phi_A[t]\in[0,1]} \phi_A[t]r_{AS}[t] + \bar{v}(Q[t] + \phi_A[t]r_{AS}[t])[t]. \quad (44)$$

- *Case 3:* $r_A[t] \leq r_A^{\min}$ and $r_B[t] > r_B^{\min}$: $\phi_A^*[t] = 0, \phi_B^*[t] = \min\{1, Q[t]/r_{RS}[t]\}$.
- *Case 4:* $r_A[t] > r_A^{\min}$ and $r_B[t] > r_B^{\min}$: We have:

$$\begin{aligned}(\phi_A^*[t], \phi_B^*[t]) &= \arg\max_{\phi_A[t],\phi_B[t]\in[0,1]} \phi_A[t]r_{AS}[t] + \bar{v}(Q[t] \\ &\quad + \phi_A[t]r_{AS}[t] - \phi_B[t]r_{RS}[t])[t] \\ &\quad \texttt{s.t.:}\ \phi_B[t]r_{RS}[t] \leq Q[t] + \phi_A[t]r_{AS}[t], \\ &\quad \phi_A[t] + \phi_B[t] = 1. \end{aligned} \quad (45)$$

Alice and Ray transmit depending on $\phi_A^*[t]$, and $\phi_B^*[t]$.

- *Updating phase:* We carry out the following updates.
  - *Queue state update:* The queue state is updated as follows:

$$Q[t+1] = Q[t] + \phi_A^*[t]r_{AS}[t] - \phi_B^*[t]r_{RS}[t]. \quad (46)$$

  - *Value function update:* We update the value function $\bar{v}(Q)$ as:

$$\begin{aligned}\bar{v}(Q)[t+1] &= (1-\kappa[t])\bar{v}(Q)[t] \\ &\quad + \kappa[t]\Bigg(\max_{\phi_A[t],\phi_B[t]} \phi_A[t]r_{AS}[t] - \beta[t]Q + \bar{v}(Q \\ &\quad + \phi_A[t]r_{AS}[t] - \phi_B[t]r_{RS}[t])[t] - \bar{v}(Q_0)[t]\Bigg). \end{aligned} \quad (47)$$

  - *Multiplier update:* The Lagrange multiplier is updated as follows:

$$\beta[t+1] = \Big[\beta[t] + \nu[t](\bar{Q}^{\max} - Q[t])\Big]_0^L$$

  for large $L > 0$.

The learning rate sequences $\kappa[t]$ and $\nu[t]$ satisfy the following properties [34]:

$$\sum_{t=1}^{\infty}\kappa[t] = \sum_{t=1}^{\infty}\nu[t] = \infty; \quad \sum_{t=1}^{\infty}(\kappa[t])^2 + (\nu[t])^2 < \infty;$$
$$\lim_{t\to\infty}\frac{\nu[t]}{\kappa[t]} = 0. \quad (48)$$

It is worth noting that we have updated the value function $\bar{v}(Q)[t]$ for all Q in (47), not only for the previously visited queue state $Q[t]$ as in conventional reenforcement learning algorithms [39]. Such batch update is possible since the random channel processes are independent of the queue state [43]. The resulting advantageous are faster convergence and concavity preservation of the value function $\bar{v}(Q)[t]$. The convergence and optimality of the online transmission algorithm is summarized in the following theorem.

Theorem 2: $\bar{v}(Q)[t], \forall t$ is concave decreasing with increasing Q. Moreover, $\lim_{t\to\infty}\bar{v}(Q)[t] = \bar{v}(Q)$ and $\lim_{t\to\infty}\beta[t] = \beta^*$ where β^* is the optimal solution of (37).

Proof: The concave decreasing property of $\bar{v}(Q)[t], \forall t$ can be proved analogously using arguments in the proof of Lemma 1. The convergence and optimality of the algorithm follow from the results in stochastic approximation theory and two-time scale analysis [34], [44]. ■

We emphasize that the if we had updated only $\bar{v}(Q[t])[t]$ in each frame t, $\bar{v}(Q)[t]$ would not be concave decreasing although it will eventually converge to the concave decreasing function $\bar{v}(Q)$. We can see that due to concavity preservation, the problems (44) and (45) are convex optimization problems.

We can see that the primal variables and the dual Lagrange multiplier are iterated simultaneously albeit on different timescales. The latter is updated at a slower timescale than the former. As seen from the slower timescale variable, the faster timescale variables appear to be equilibrated to the optimal values corresponding to its current value. Also, as viewed from the faster timescale variables, the slower timescale variable appears to be almost constant. Such two timescales updates converge to the optimal solution of (37).

VI. Results Illustration and Discussions

A. System Configurations

Consider Rayleigh fading channels. Assume the distance from Alice to Bob is normalized to 1. Under dual-hop relaying, we assume Alice, Ray, and Bob are located on a straight line. In that case, let us denote the distances between Alice and Ray and between Ray and Bob as $d_{R,x} \in (0,1)$ and $1 - d_{R,x} \in (0,1)$, respectively. In a 2-D plane, we can assume Alice, Ray, and Bob are located at points with coordinates $(0,0)$, $(d_{R,x}, 0)$, and $(1,0)$, respectively.

Denote the average channel power gain of the Alice–Bob link as $\bar{h}_{AB}$. We assume $\bar{h}_A = \bar{h}_{AB}/d_{R,x}^{\gamma}$, and $\bar{h}_B = \bar{h}_{AB}/(1-d_{R,x})^{\gamma}$ where γ is the path-loss exponent. In the following, we choose $\gamma = 2$.

Eve is assumed to be located at point with coordinate $(d_{E,x}, d_{E,y})$, $d_{E,x}, d_{E,y} > 0$. Hence, the distances between Alice and Eve and between Ray and Eve can be computed as $d_{AE} = (d_{E,x}^2 + d_{E,y}^2)^{1/2}$, and $d_{RE} = ((d_{E,x} - d_{R,x})^2 + d_{E,y}^2)^{1/2}$, respectively. Hence, using the path-loss model, we have $\bar{h}_{AE} = \bar{h}_{AB}/d_{AE}^{\gamma}$, and $\bar{h}_{RE} = \bar{h}_{AB}/d_{RE}^{\gamma}$.

W.l.o.g., we normalize $\bar{h}_{AB} = 0$ dB.

B. Delay-Unconstrained Communication

We first look at the throughputs of the transmission schemes assuming delay-unconstrained communication.

1) Fixed Power Allocation: We assume fixed Eve location where $d_{E,x} = d_{E,y} = 1.5\sqrt{2}/2$ (hence, $d_{AE} = 1.5$). In this case, the eavesdropper Alice–Eve link is 3.52 dB less than the main Alice–Bob link.

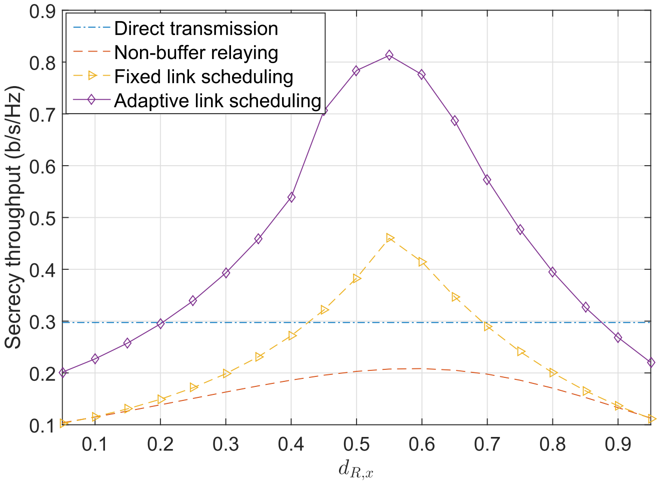
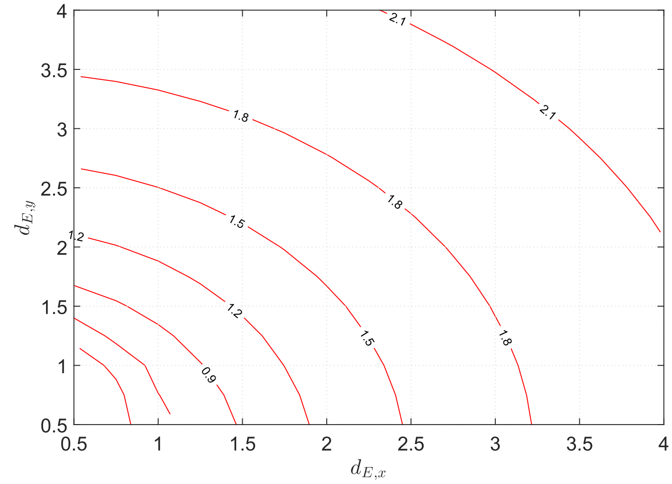
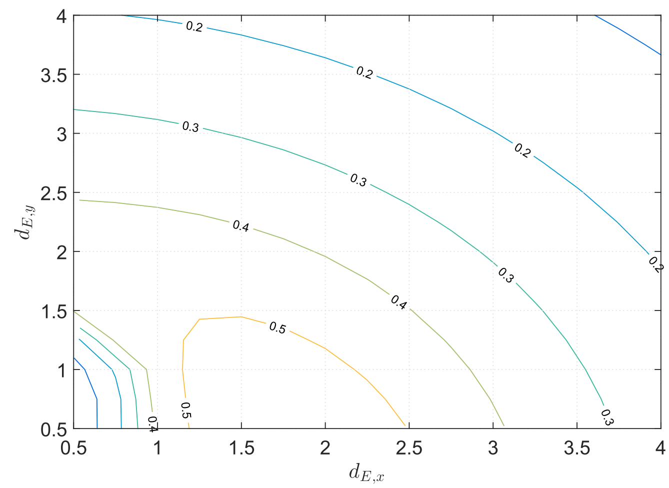


Fig. 2. Throughput versus Ray location $d_{R,x}$.



(a) Throughput of the ALS scheme



(b) Throughput gains of the ALS over direct transmission schemes

Fig. 3. Contour throughput plots versus Eve location $(d_{E,x}, d_{E,y})$.

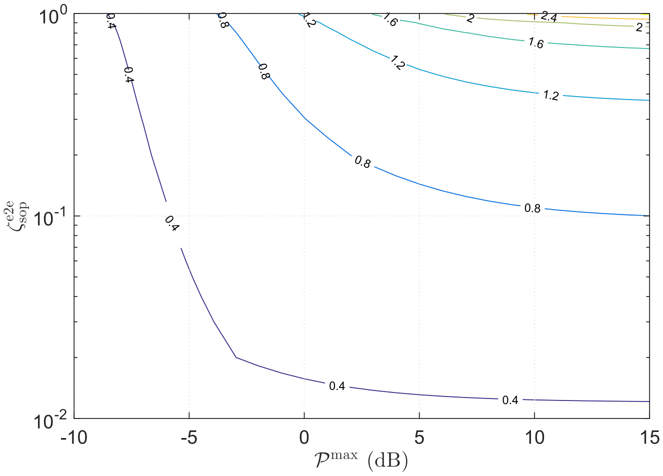
We first investigate the effects of Ray location on the performance of the transmission schemes. Let $\mathcal{P}^{\max} = 10$ dB and $\zeta_{\text{sop}}^{\text{e2e}} = 10^{-1}$. We plot the throughputs of the transmission schemes versus $d_{R,x} \in (0,1)$ in Fig. 2. The throughput of the direct Alice–Bob transmission scheme is independent of $d_{R,x}$, and is constant. We can see that ALS scheme significantly outperforms FLS and non-buffer relaying schemes due to its capability to exploit the fading diversity (and buffer-aided relaying capability) for transmission scheduling. Moreover, it can be observed that Ray location has profound effects on the performance of the relaying schemes. When Ray is deployed near Alice or Bob, ALS scheme performs worse than direct transmission. This is because one of the main channels is not much improved. However, when Ray is located toward mid-way between Alice and Bob, ALS scheme attains superior throughput gains over direct transmission. In this case, the signal strengths of both of the main A–R and R–B channels are (much) stronger than the eavesdropper A–E and R–E channels.

The above experiment shows that deploying Ray equidistant between Alice and Bob attains good (although not necessarily optimal) throughput for relaying schemes. Hence, in the following, we assume $d_{R,x} = .5$ and focus on the performance of ALS scheme only.

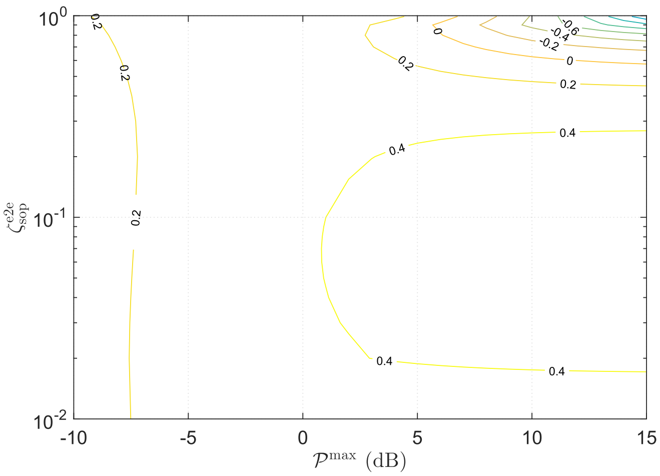
We should emphasize that the potential throughput gains (or even losses) of relaying transmission over direct transmission also depend largely on Eve location (and hence, signal strengths of the eavesdropper channels). Hence, in the next experiment, we change the possible locations $(d_{E,x}, d_{E,y})$ of Eve. Fig. 3 shows the contour throughput plots of ALS scheme versus $(d_{E,x}, d_{E,y})$. As Eve is farther away from Alice, the eavesdropper channels become weaker, and hence, the throughput is increased. Also, the increasing rate of throughput decreases with increasing Eve distances. Note that when Eve is very far away (i.e., $\bar{h}_{AE}, \bar{h}_{RE} \to 0$), the throughput approaches the maximum throughput of ALS scheme without Eve [27]. Fig. 3 also displays the throughput gains of the ALS scheme over direct transmission scheme. We can see that the gains are smaller when Eve is closer or farther from Alice. In the former case, since the eavesdropper channels are very strong, deploying Ray does not result in much improved main channels (relatively compared with the eavesdropper channels). In the latter case, direct transmission is efficient since the risk of secrecy outage is small.

Next, let $d_{E,x} = d_{E,y} = 1.5\sqrt{2}/2$. In Fig. 4, we show the contour throughput plots of ALS scheme and its throughput gains/losses over direct transmission versus $\zeta_{\text{sop}}^{\text{e2e}}$ and $\mathcal{P}^{\max}$. As $\mathcal{P}^{\max}$ increases and/or the secrecy constraint becomes less stringent, higher throughputs can be attained as expected. As the secrecy constraint becomes very stringent, very small throughputs can be supported even with large $\mathcal{P}^{\max}$. Also, as $\zeta_{\text{sop}}^{\text{e2e}}$ approaches 0, positive throughputs cannot be supported. Compared with direct transmission scheme, the ALS scheme is more advantageous except for sufficiently large $\mathcal{P}^{\max}$ and loose secrecy constraints.

2) Adaptive Power Allocation: We assume that $d_{AE} = d_{RE} = d_E = 1.5$, i.e., Eve is equidistant from Alice and Ray. Fig. 5 plots the throughputs of the ALS schemes with fixed and adaptive power allocation versus $\zeta_{\text{sop}}^{\text{e2e}}$ for two values of $\mathcal{P}^{\max} = -10$ dB, or 0 dB. We can observe that for each $\mathcal{P}^{\max}$,



(a) Throughput of the ALS scheme



(b) Throughput difference between the ALS and direct transmission schemes

Fig. 4. Contour throughput plots versus $(\mathcal{P}^{\max}, \zeta_{\text{sop}}^{\text{e2e}})$.

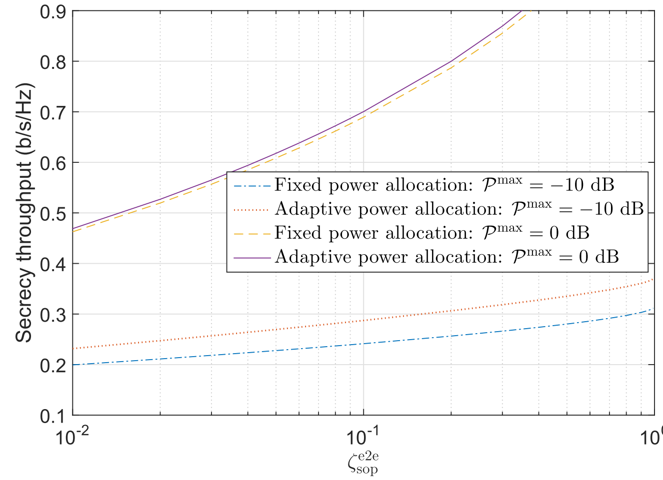


Fig. 5. Throughput versus $\zeta_{\text{sop}}^{\text{e2e}}$.

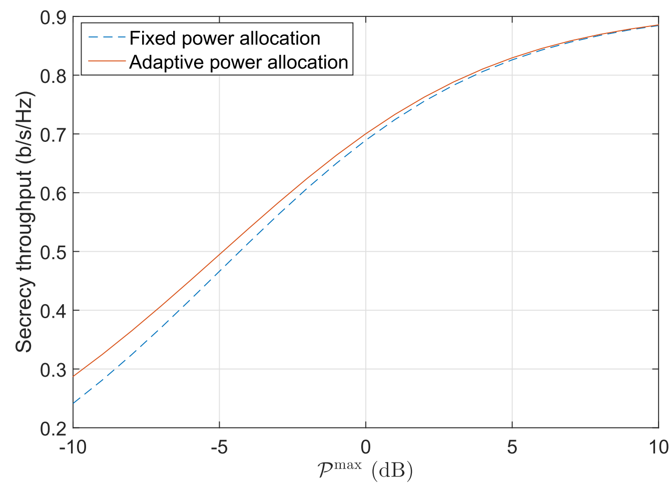


Fig. 6. Throughput versus $\mathcal{P}^{\max}$.

the gains due to adaptive power allocation remain almost constant over all values of $\zeta_{\text{sop}}^{\text{e2e}}$. It seems that the gains are more significant for smaller $\mathcal{P}^{\max}$, which are demonstrated in the next experiment.

Next, fix $\zeta_{\text{sop}}^{\text{e2e}} = 10^{-1}$. Fig. 6 plots the throughputs of ALS schemes with fixed and adaptive power allocation versus $\mathcal{P}^{\max}$. We can observe that the gains due to adaptive power allocation are more noticeable at low SNRs than at high SNRs. Since the secrecy rate function is concave increasing with power, adaptive power allocation is more effective at low SNRs to vary the secrecy rates. At high SNRs, varying the power will not affect much the secrecy rates.

C. Delay-Constrained Communication

In the following, we look at the throughputs under average delay constraint consideration.

1) A Sub-Optimal Transmission Scheme: A transmission scheme guaranteeing bounded average delay can be developed by heuristically modifying the ALS scheme developed in Section III for the delay-unconstrained case as follows.

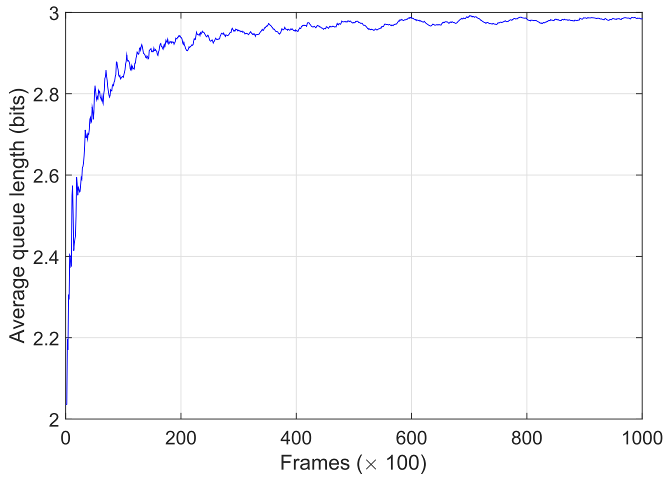
Consider the transmission scheme $(\phi_A^\sharp[t], \phi_B^\sharp[t])$. In frame t, Alice or Ray transmits with secrecy rates $r_{AS}^\sharp[t] = r_{AS}[t]$, and $r_{RS}^\sharp[t] = r_{RS}[t]$, respectively when he/she is the only transmitter satisfying the secrecy constraint. When both Alice and Bob satisfy the secrecy constraint, (i.e., $r_A[t] > r_A^{\min}$, and $r_B[t] > r_B^{\min}$), the following link scheduling solution is used:

$$(\phi_A^\sharp[t], \phi_B^\sharp[t]) = \begin{cases} (1,0), & r_{AS}[t] \geq \chi^\sharp r_{RS}[t], \\ (0,1), & \text{otherwise.} \end{cases} \quad (49)$$

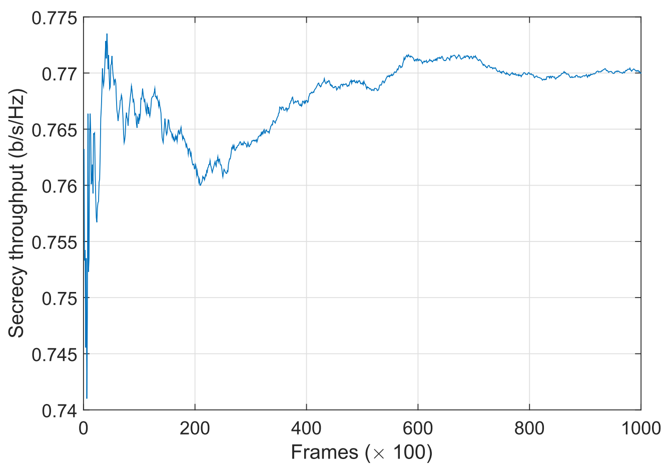
for $\chi^\sharp > \chi^*$ where χ^* satisfies (14). As a result, we can see that the average arrival rate to Ray buffer is strictly smaller than the average service rate. Hence, by *Remark 1*, the throughput is equal to the average arrival rate:

$$\tau^\sharp(\chi^\sharp) = \mathbb{E}[\phi_A^\sharp[t] r_{AS}[t]].$$

We can easily see that $\tau^\sharp(\chi^\sharp)$ decreases with increasing $\chi^\sharp > \chi^*$. More importantly, this scheme results in finite (average) queue length $\mathbb{E}[Q[t]]$ (or finite average delay), where smaller $\chi^\sharp$ induces larger $\mathbb{E}[Q[t]]$ and as $\chi^\sharp \to \chi^*$, $\mathbb{E}[Q[t]] \to \infty$. We use simulation results to obtain the time-averaged $\mathbb{E}[Q[t]]$ and throughput of this scheme for a given $\chi^\sharp$.



(a) Time-averaged queue length



(b) Throughput

Fig. 7. Convergence of the online transmission algorithm.

2) Convergence of the Proposed Iterative Online Algorithm: Assume $d_{AE} = d_{RE} = 1.5$, $\zeta_{\rm sop}^{\rm e2e} = 10^{-1}$, and $\mathcal{P}^{\max} = 10$ dB. Also, $\bar{Q}^{\max} = 3$ (bits). Fig. 7 shows the convergence of the time-average queue length $\frac{1}{t}\sum_{\tau=1}^{t} Q[\tau]$, and throughput $\frac{1}{t}\sum_{\tau=1}^{t} \phi_A[\tau] r_{AS}[\tau]$. We can see that the time-average queue length approaches $\bar{Q}^{\max}$ as expected, i.e., the queue length constraint is satisfied. The online transmission algorithm can be sub-optimal at the beginning but it converges to the (neighborhood of the) optimal solution after sufficient time. By changing the learning step-size sequences, we can affect the convergence rate. However, this is out of the scope of this work. We re-emphasize that the online transmission algorithm does not need to know the fading distributions of the main A–R and R–B channels.

3) Throughput Performance: For unconstrained delay case, we have $\chi^* = 1$ and the corresponding throughput $\tau^*(\infty) = .8845$, which is the upper bound for the achieved throughputs of transmission schemes with finite average delay.

In Fig. 8, we plot the throughputs of the proposed online algorithm and heuristic transmission algorithm described previously versus average queue length $\mathbb{E}[Q[t]]$. We can see that the throughput-queue length trade-off curve is concave

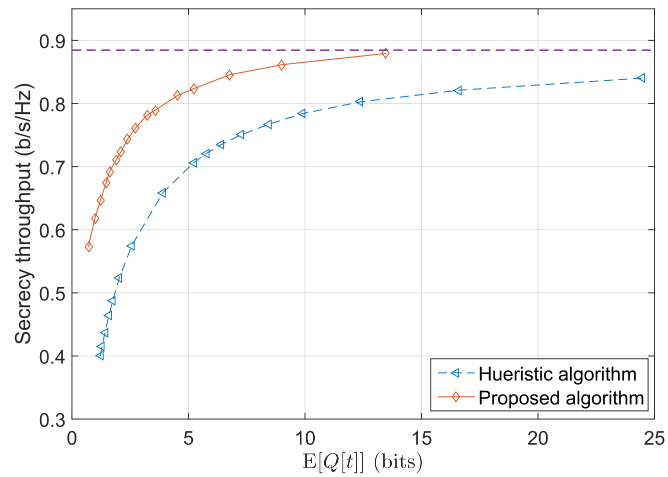


Fig. 8. Secrecy throughput versus $\mathbb{E}[Q[t]]$.

increasing as analytically proved in Theorem 1. Moreover, it can be observed that the proposed algorithm attains higher throughput (for an average delay) and smaller delay (for a throughput) than the heuristic algorithm. With optimal resource allocation, a throughput close to $\tau^*(\infty)$ can be achieved with the average queue length being slightly smaller than 14 (bits). On the other hand, with the sub-optimal algorithm, the queue length would be much larger. By taking into account the buffer state to schedule Alice's and Ray's transmissions, the proposed algorithm can achieve the optimal throughput-delay trade-off.

VII. Conclusions

In this work, we have considered Alice-Ray-Bob relaying communications over fading channels, where Ray has possibly been placed to difference locations. We have developed various secure transmission schemes in terms of secrecy outage, under the assumption of a passive Eve, who monitors both Alice's and Ray's transmissions. Toward practical secure communications, we have also assumed that only the statistics of the eavesdropper channels are available to the transmitters (in addition to the CSI of the main channels). We have developed the throughput–optimal ALS for two scenarios: 1) fixed (Alice and Ray) power allocation; and 2) adaptive power allocation by solving constrained optimization problems using Lagrangian approach and convex optimization. We have shown that in each frame, either Alice or Ray or neither is scheduled for transmission depending on the instantaneous CSI of the main channels. Since the transmission schemes can result in unbounded queueing delay at Ray's buffer, we have also developed transmission schemes guaranteeing bounded average delay using stochastic control and MDP approach. An transmission algorithm has been proposed, which does not require prior information on the channel fading distributions and converges to the optimal solution. Simulation results demonstrate the effectiveness of the developed transmission schemes over several benchmark schemes over wide ranges of secrecy requirements and SNR regions.

APPENDIX
PROOFS

A. Proof of Theorem 1

That $\tau^*(\bar{Q})$ is increasing with $\bar{Q}$ is straightforward. As the (average) queue length is allowed to be larger, Alice can transmit more data to Ray, and thus, increasing the throughput.

We show that $\tau^*(\bar{Q})$ is concave. Let $\bar{Q}^1$ and $\bar{Q}^2$ be two (average) queue lengths with corresponding optimal throughputs $\tau^*(\bar{Q}^1)$ and $\tau^*(\bar{Q}^2)$. W.l.g.o., assume $\bar{Q}^1 < \bar{Q}^2$. To show the concavity of $\tau^*(\bar{Q})$, we want to show that for any $\lambda \in [0, 1]$:

$$\tau^*(\lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2) \geq \lambda\tau^*(\bar{Q}^1) + (1-\lambda)\tau^*(\bar{Q}^2). \quad (50)$$

We will prove this using sample path arguments [33]. Let $\{h_i[t](w)\}_{t=1}^{\infty}, i \in \{A, B\}$ be given sample paths of the channel states where w denotes sample path index. Let $\{\phi_i^1[t](w)\}_{t=1}^{\infty}, i \in \{A, B\}$ be sequences of (optimal) allocation solutions which attain $\tau^*(\bar{Q}^1)$. Let $\{Q^1[t](w)\}_{t=1}^{\infty}$ be the corresponding sequence of buffer states. Likewise, let $\{\phi_i^2[t](w)\}_{t=1}^{\infty}, i \in \{A, B\}$ be the sequences of allocation solutions which attain $\tau^*(\bar{Q}^2)$. Let $\{Q^2[t](w)\}_{t=1}^{\infty}$ be the corresponding sequence of buffer states. We have:

$$\lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \phi_A^k[t](w) r_{AS}[t](w) = \tau^*(\bar{Q}^k),$$
$$\lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} Q^k[t](w) = \bar{Q}^k$$

for $k = 1, 2$. Now consider the $\lambda-$policy, a new sequences of allocation solutions, $\{\phi_i^{\lambda}[t](w)\}_{t=1}^{\infty}, i \in \{A, B\}$ where:

$$\phi_i^{\lambda}[t](w) = \lambda\phi_i^1[t](w) + (1-\lambda)\phi_i^2[t](w), \forall t, i \in \{A, B\}. \quad (51)$$

Let $\{Q^{\lambda}[t](w)\}_{t=1}^{\infty}$ be the sequence of buffer states under $\lambda-$policy. From (51), we can see that $\phi_A^{\lambda}[t](w) + \phi_B^{\lambda}[t](w) \leq 1, \forall t$. Hence, $\lambda-$policy is feasible.

We now look at the throughput and (average) queue length achieved by $\lambda-$policy.

First, from (51), the throughput of the $\lambda-$policy can be computed as:

$$\begin{aligned}\tau^{\lambda} &= \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} \phi_A^{\lambda}[t](w) r_{AS}[t](w) \\ &= \lambda\tau^*(\bar{Q}^1) + (1-\lambda)\tau^*(\bar{Q}^2). \end{aligned} \quad (52)$$

Assume $Q^{\lambda}[1](w) = Q^1[1](w) = Q^2[1](w) = 0$. By definition, for $t = 1, 2, \ldots$, we have:

$$\begin{aligned}Q^k[t+1](w) = Q^k[t](w) &+ \phi_A^k[t](w) r_{AS}[t](w) \\ &- \phi_B^k[t](w) r_{RS}[t](w), \quad k = 1, 2.\end{aligned}$$

Note that in the proof of the following Lemma 1, we show that optimal transmission solutions have: $\phi_B^k[t](w) r_{RS}[t](w) \leq Q^k[t](w) + \phi_A^k[t](w) r_{AS}[t](w), k = 1, 2$.

Then, using recursion, we can show that:

$$Q^{\lambda}[t](w) = \lambda Q^1[t](w) + (1-\lambda) Q^2[t](w), \quad \forall t.$$

The average queue length achieved by the $\lambda-$policy is computed as:

$$\bar{Q}^{\lambda} = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{t=1}^{\mathcal{T}} Q^{\lambda}[t](w) = \lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2.$$

We have seen that the $\lambda-$policy achieves throughput $\tau^{\lambda} = \lambda\tau^*(\bar{Q}^1) + (1-\lambda)\tau^*(\bar{Q}^2)$ and queue length $\bar{Q}^{\lambda} = \lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2$. Moreover, the optimal solution with queue length $\lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2$ can achieve throughput $\tau^*(\lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2)$, which is at least equal to τ^{λ}. Thus, we must have:

$$\tau^*(\lambda\bar{Q}^1 + (1-\lambda)\bar{Q}^2) \geq \lambda\tau^*(\bar{Q}^1) + (1-\lambda)\tau^*(\bar{Q}^2)$$

as desired. We conclude that $\tau^*(\bar{Q})$ is concave increasing with increasing $\bar{Q}$. This completes the proof. ■

B. Proof of Lemma 1

We can intuitively see that $\bar{v}(Q)$ is decreasing with Q since as Q increases, less data is allowed to enter the Ray buffer to avoid delay constraint violation. Consequently, smaller throughput can be attained. More rigorous argument is as below.

We use induction to show that $\bar{v}(Q)[t+1]$ is concave (decreasing) function using the RVIA equation (43). Initialize $\bar{v}(Q)[1]$ with some concave (decreasing) function. Assume that $\bar{v}(Q)[t]$ is concave (decreasing) for some $t = 2, 3, \ldots$. Consider the function inside the integral in (43) for some fixed h_A, and h_B:

$$\begin{aligned}\hat{v}(Q; h_A, h_B)[t] = \max_{\phi_A, \phi_B} \quad & \phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} \\ & - \min\{Q + \phi_A r_{AS}, \phi_B r_{RS}\})[t]. \end{aligned} \quad (53)$$

We will show that $\hat{v}(Q; h_A, h_B)[t]$ is concave (decreasing) by considering the following cases.

Case 1: $h_A \leq h_A^{\min}$ and $h_B \leq h_B^{\min}$: $\phi_A^* = \phi_B^* = 0$. Then, we have:

$$\hat{v}(Q; h_A, h_B)[t] = -\beta Q + \bar{v}(Q)[t] \quad (54)$$

which is a concave (decreasing) function.

Case 2: $h_A > h_A^{\min}$, and $h_B \leq h_B^{\min}$. Then, we have:

$$\hat{v}(Q; h_A, h_B)[t] = \max_{\phi_A \in [0,1]} \phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS})[t]. \quad (55)$$

The objective function is (jointly) concave in (ϕ_A, Q). Hence, $\hat{v}(Q; h_A, h_B)[t]$ is concave in Q since the partial maximization of the concave function is also concave.

Case 3: $h_A \leq h_A^{\min}$, and $h_B > h_B^{\min}$. Then, we have:

$$\hat{v}(Q; h_A, h_B)[t] = \max_{\phi_B \in [0,1]} -\beta Q + \bar{v}(Q - \min\{Q, \phi_B r_{RS}\})[t].$$

Due to the decreasing assumption of $\bar{v}(Q)[t]$, we have $\phi_B^* = \min\{1, Q/r_{RS}\}$, and hence:

$$\hat{v}(Q; h_A, h_B)[t] = \begin{cases} -\beta Q + \bar{v}(0)[t], & Q \leq r_{RS}, \\ -\beta Q + \bar{v}(Q - r_{RS})[t], & \text{otherwise} \end{cases}$$

which is concave (decreasing).

Case 4: $h_A > h_A^{\min}$, and $h_B > h_B^{\min}$. Then, we have:

$$\hat{v}(Q; h_A, h_B)[t] = \max_{\phi_A, \phi_B} \ \phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} - \min\{Q + \phi_A r_{AS}, \phi_B r_{RS}\})[t]. \quad (56)$$

This problem is equivalent to the following problem:

$$\hat{v}(Q; h_A, h_B)[t] = \max_{\phi_A, \phi_B} \ \phi_A r_{AS} - \beta Q + \bar{v}(Q + \phi_A r_{AS} - \phi_B r_{RS})[t] \quad (57)$$

with an additional constraint $\phi_B r_{RS} \leq Q + \phi_A r_{AS}$. We can now see that the objective function is (jointly) concave in (ϕ_A, ϕ_B, Q). Hence, $\hat{v}(Q; h_A, h_B)[t]$ is concave in Q since the partial maximization of the concave function is also concave.

We conclude that $\hat{v}(Q; h_A, h_B)[t]$ is concave decreasing. Then, from (43), we have $\bar{v}(Q)[t+1]$ is concave decreasing since the expectation preserves the decreasing concavity. As $\lim_{t \to \infty} \bar{v}(Q)[t+1] = \bar{v}(Q)$, we conclude that $\bar{v}(Q)$ is concave decreasing with Q. ∎

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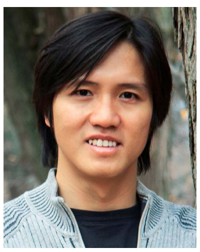

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