Exploiting Large-Scale MIMO Techniques for Physical Layer Security with Imperfect Channel State Information

Xiaoming Chen†‡, Chau Yuen*, Zhaoyang Zhang*
† College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, China.
‡ National Mobile Communications Research Laboratory, Southeast University, China.
* Singapore University of Technology and Design, Singapore.
Email: chenxiaoming@nuaa.edu.cn, yuenchau@sutd.edu.sg, ning_ming@zju.edu.cn

Abstract—In this paper, we study the problem of physical layer security in large-scale multiple input multiple output (LS-MIMO) systems. The large number of antenna elements in LS-MIMO system is exploited to enhance transmission security and improve system performance, especially when the eavesdropper is closer to the information source and has more antennas than the legitimate user. However, in practical systems, the problem becomes challenging because the eavesdropper channel state information (CSI) is usually unavailable without cooperation and the legitimate CSI may be imperfect due to channel estimation error. In this paper, we first analyze the performance of physical layer security without eavesdropper CSI and with imperfect legitimate CSI, and then propose an energy-efficient power allocation scheme to meet the demand for wireless security and quality of service (QoS) simultaneously. Finally, numerical results validate the effectiveness of the proposed scheme.

I. INTRODUCTION

The broadcast nature of wireless channels enables the freedom to communicate at anywhere, but also leads to information leakage. Traditionally, information security is realized by using cryptography technology. In fact, secrecy transmission can be realized through physical layer security by exploiting the channel fading and noise, which avoids the utilization of cryptography methods [1]-[2]. In brief, as long as the eavesdropper channel is degraded, it is likely to provide the secure transmission based on physical layer security.

The performance of physical layer security is usually measured by secrecy rate, defined as the difference between the legitimate channel capacity and the eavesdropper channel capacity [3]. It is generally known that multi-antenna system can improve the desired channel capacity and impair the undesired channel capacity simultaneously by making use of its unique spatial degrees of freedom. Thus, physical layer security combining with multi-antenna techniques draws considerable research attentions [4]-[6]. In [7] and [8], the optimal beamforming design methods for MISO and MIMO wiretap channels were given by maximizing the secrecy rate respectively, assuming that the multi-antenna information source had full legitimate and eavesdropper channel state information (CSI). However, in practical systems, the eavesdropper CSI is difficult to be obtained. It is proved that if there is no eavesdropper CSI and no artificial noise in the transmit signals, the beamforming along the direction of the legitimate channel is optimal [9] [10]. In this case, since the source has no knowledge of the eavesdropper channel that varies randomly, it is impossible to maintain a steady secrecy rate over all realization over fading channels. Hence, the secrecy outage capacity is adopted as a useful and intuitive metric to evaluate security, which is defined as the maximum available rate under the condition that the probability that the real transmission rate is greater than the secrecy rate is equal to a given value [11] [12].

In addition to the achievement of CSI, there are other problems to be solved in physical layer security. For example, the eavesdropper may be closer to the information source and has more antennas than the secure user (SU), such that the secrecy outage capacity is quite small in order to guarantee the security. In this context, even though the multi-antenna gain is exploited, it will be a challenging task to realize a secure, reliable and efficient information transmission with traditional multi-antenna techniques. Recently, the concept of large-scale MIMO (LS-MIMO) has been proposed to significantly improve the performance by taking advantage of its large array gain [13]. Intuitively, due to the high spatial resolution of LS-MIMO systems, the information leaked to the eavesdropper is very small. Thus, the information security can be achieved with a high probability. Inspired by this, we introduce the LS-MIMO technique into physical layer security. As shown later, by increasing the number of antennas at the information source, stringent security requirement can be met even with high QoS constraint.

However, the use of LS-MIMO is not without challenge. In LS-MIMO systems, the transmitter commonly obtains the CSI via channel reciprocity in time division duplex (TDD) systems [14]. However, due to a large number of antenna elements in LS-MIMO systems, channel estimation error is inevitable, resulting in CSI mismatch and thus performance loss [15]. In
this paper, we will investigate the effect of imperfect CSI in LS-MIMO systems on the secrecy outage capacity.

In addition, it is also important for a wireless communications system to guarantee a certain quality of service (QoS). In traditional MIMO systems, QoS can always be met by increasing the transmit power; however, this is not the case in a physical layer security system. In secure communications based on physical layer security, the secrecy outage capacity is not an increasing function of transmit power any more, since both legitimate and eavesdropper channel capacities improves as transmit power increases \([16]\). Therefore, it makes sense to distribute the power according to channel conditions, e.g. interception distance. In this paper, we propose an energy-efficient power allocation scheme by maximizing the ratio of secrecy outage capacity and power consumption, namely energy efficiency (bits per Joule), while fulfilling security and QoS requirements.

The rest of this paper is organized as follows. We first give an overview of the secure LS-MIMO system and investigate the impact of imperfect CSI on the secrecy outage capacity in Section II, and then derive an energy-efficient power allocation scheme by maximizing the secrecy energy efficiency while satisfying the secrecy, QoS and power constraints in Section III. In Section IV, we present some numerical results to validate the effectiveness of the proposed scheme. Finally, we conclude the whole paper in Section V.

II. SYSTEM MODEL

![Fig. 1. An overview of the secure LS-MIMO system model.](image)

We consider an LS-MIMO downlink, where a base station (BS) with \(N_t\) antennas communicates with a single antenna secure user (SU), while a passive eavesdropper with \(N_r\) antennas also receives the signal from the BS due to the broadcast nature of the wireless channel, and tries to detect the message. Note that the number of BS antennas \(N_t\) can be very large in an LS-MIMO system. We use \(\mathbf{h}\) to denote the \(N_t\) dimensional legitimate channel vector from the BS to the SU, where \(\mathbf{h}\) is a circularly symmetric complex Gaussian (CSCG) random vector with zero mean and unit variance. Similarly, we use \(\alpha \mathbf{G}\) to denote the \(N_r \times N_t\) eavesdropper channel matrix from the BS to the eavesdropper, where \(\alpha\) is the relative path loss and \(\mathbf{G}\) is the small scale fading matrix with i.i.d. zero mean and unit variance complex Gaussian entries, respectively. Note that a large \(\alpha\) means that the eavesdropper is close to the BS, and thus the interception ability of the eavesdropper is strong. If \(\alpha = 1\), the eavesdropper has the same access distance as the SU. It is assumed that \(\alpha\) remains constant during a relatively long time period due to its slow fading and is known at the BS, while \(\mathbf{h}\) and \(\mathbf{G}\) remain constant in a time slot and independently fade slot by slot. The network is operated in time division duplex (TDD) mode, so the channel reciprocity holds true.

At the beginning of each time slot, the SU transmits the pilot for channel estimation at the BS. Due to a large number of antennas and limited channel estimation capacity, there may be channel estimation error. Commonly, the CSI mismatch caused by estimation error can be modeled as \([17]\)

\[
\mathbf{h} = \sqrt{\rho} \hat{\mathbf{h}} + \sqrt{1 - \rho} \mathbf{e},
\]

where \(\hat{\mathbf{h}}\) is the estimated CSI with the same distribution as \(\mathbf{h}\), and \(\mathbf{e}\) is the estimation error noise with i.i.d. zero mean and unit variance complex Gaussian entries. \(\rho\), scaling from 0 to 1, is the correlation coefficient between \(\mathbf{h}\) and \(\hat{\mathbf{h}}\). The larger the correlation coefficient, the more accurate the estimation. If \(\rho = 1\), the BS has perfect CSI. We assume the BS knows the statistics \(\rho\). Note that the BS always has partial CSI by making use of channel reciprocity, so we do not consider the case of \(\rho = 0\) in this paper.

According to the estimated CSI \(\hat{\mathbf{h}}\), the BS performs maximum ratio transmission (MRT), namely designing the transmit beam \(\mathbf{w} = \frac{\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\). Thus, the received signals at the SU and the eavesdropper are given by

\[
y_s = \sqrt{P} \mathbf{h}^H \mathbf{w} x + n_s
\]

and

\[
y_e = \sqrt{P} \alpha \mathbf{G} \mathbf{w} x + n_e,
\]

respectively, where \(x\) is the Gaussian distributed transmit signal with unit variance, \(P\) is the transmit power, \(n_s\) and \(n_e\) are the additive Gaussian white noises with unit variance at the SU and the eavesdropper, respectively. While there are many available methods to detect the intercepted signal \(y_e\), at the eavesdropper, e.g. antenna selection (AS), maximum ratio combination (MRC), zero-forcing (ZF) and minimum mean square error (MMSE), we only consider the AS in this paper. Specifically, during each time slot, the eavesdropper selects one antenna with the strongest gain to receive and detect the intercepted signal. Hence, the capacities of the legitimate and eavesdropper channels can be expressed as

\[
C_s = W \log_2(1 + \gamma_s)
\]

and

\[
C_e = W \log_2(1 + \gamma_e),
\]

where \(W\) is the spectrum bandwidth, \(\gamma_s = P \|\mathbf{h}^H \mathbf{w}\|^2\) and \(\gamma_e = \max_{1 \leq i \leq N_r} P \alpha^2 \|g_i \mathbf{w}\|^2\) are the signal-to-noise ratio (SNR) at the
SU and the eavesdropper respectively, and \( g_i \) is the \( i \)th row of \( G \). For the legitimate channel capacity \( C_s \) in an LS-MIMO system with imperfect CSI, we have the following lemma:

**Lemma 1**: As \( N_t \) approaches infinity, the legitimate channel capacity \( C_s \) asymptotically approaches \( W \log_2(\rho P N_t) \).

**Proof**: Please refer to the Appendix.

From an information-theoretic view, the secrecy rate is given by \( C_{sec} = [C_s - C_e]^+ \), where \([x]^+ = \max(x, 0)\). Since there is no knowledge of the eavesdropper channel at the BS, it is impossible to maintain a steady secrecy capacity over all realizations over fading channels. In this paper, we take the secrecy outage capacity \( R_{sec} \) as the performance metric, which is defined as the maximum achievable rate under the condition that the outage probability that the transmission rate surpasses the secrecy rate is equal to a given value \( \varepsilon \), namely

\[
P_r (R_{sec} > C_s - C_e) = \varepsilon.
\] (6)

Substituting (5) and (27) into (6), the outage probability can be transformed as

\[
\varepsilon = P_r \left( \gamma_e > \rho PN_t 2^{-R_{sec}/W} - 1 \right)
= 1 - F_{\gamma_e} \left( \rho PN_t 2^{-R_{sec}/W} - 1 \right),
\] (7)

where \( F_{\gamma_e}(x) \) is the cumulative distribution function (cdf) of \( \gamma_e \). Since \( w \) is independent of \( g_j \) for an arbitrary \( j \), \( |g_j^* w|^2 \) is exponentially distributed. Thus, according to the order theory, we have

\[
F_{\gamma_e}(x) = \left( 1 - \exp \left( -\frac{x}{P\alpha^2} \right) \right)^{N_t}.
\] (8)

Substituting (8) into (7), it is obtained that

\[
\varepsilon = 1 - \left( 1 - \exp \left( -\frac{\rho PN_t 2^{-R_{sec}/W} - 1}{P\alpha^2} \right) \right)^{N_t}.
\] (9)

**Remark**: The secrecy outage probability \( \varepsilon \) is a monotonically increasing function of \( N_t \) and a monotonically decreasing function of \( N_e \). As \( N_t \) increases, the secrecy outage probability \( \varepsilon \) will increase for a given secrecy outage capacity \( R_{sec} \). To solve this problem, by letting \( N_t \to \infty \), \( \varepsilon \) asymptotically approaches 0, the security requirement can be guaranteed nearly with probability 1. Hence, in an LS-MIMO system, when the BS is equipped with a large number of antennas, even the eavesdropper is closer to the BS (i.e. \( \alpha > 1 \)) and has more antennas than the SU, the BS can still support a high transmission rate with a low outage probability, and then meets both secrecy and QoS requirements.

Given transmit power \( P \) and the requirement of outage probability \( \varepsilon \), the secrecy outage capacity can be expressed as

\[
R_{sec} = -W \log_2 \left( \frac{1 - P\alpha^2 \ln \left( 1 - (1-\varepsilon)^{1/N_t} \right)}{\rho PN_t} \right).
\] (10)

From (9), we can also obtain the probability of positive secrecy capacity as

\[
P_r (C_{sec} > 0) = \left( 1 - \exp \left( -\frac{\rho PN_t - 1}{P\alpha^2} \right) \right)^{N_t}.
\] (11)

Intuitively, the probability \( P_r (C_{sec} > 0) \) increases as \( N_t \) increases and decreases as \( \alpha \) and \( N_e \) increase, which also proves that we can easily solve the problems that the eavesdropper is closer to the BS and has more antennas than the SU by adding the antennas at the BS in an LS-MIMO system.

### III. Energy-Efficient Power Allocation

Considering the demand for green communication, we attempt to derive a secure and efficient power allocation scheme to maximize the secrecy energy efficiency while satisfying the secrecy, QoS and power constraints, which is equivalent to the following optimization problem:

\[
J_1 : \max \quad \frac{R_{sec}}{P_0 + P}
\] (12)
\[
s.t. 
\varepsilon \leq \varepsilon_{max}
\] (13)
\[
R_{sec} \geq R_{min}
\] (14)
\[
P \leq P_{max},
\] (15)

where \( P \) is the transmit power as defined in Section II, and \( P_0 \) is the constant power consumption in the transmit filter, mixer, frequency synthesizer and digital-to-analog converter, which are independent of the actual transmit power. \( (12) \) is the so called secrecy energy efficiency, defined as the number of transmission bits per Joule. \( (13) \) is used to fulfill the secrecy requirement based on physical layer security, and \( (14) \) is the QoS constraint, where \( R_{min} \) is the minimum effective transmission rate to meet a given QoS requirement, such as delay provisioning. \( P_{max} \) is the constraint on maximum transmit power. Since \( \varepsilon \) is a monotonically increasing function of \( R_{sec} \) and a decreasing function of \( P \), the condition of \( \varepsilon = \varepsilon_{max} \) is optimal in the sense of maximizing the secrecy energy efficiency. Thus, \( (13) \) can be canceled and \( R_{sec} \) can be replaced by \(-W \log_2 \left( \frac{1-P\alpha^2 \ln \left( 1 - (1-\varepsilon_{max})^{1/N_t} \right)}{\rho PN_t} \right)\). Notice that there may be no feasible solution for \( J_1 \), due to the stringent secrecy, QoS and power constraints. Under such a condition, in order to obtain a solution, that will fulfill the requirements, we can increase the number of antennas at the BS, which is the promising advantage of the LS-MIMO system.

The objective function \( (12) \) in a fractional program is a ratio of two functions of the optimization variable \( P \), resulting in that \( J_1 \) is a fractional programming problem, which is in general nonconvex. Following \( (16) \), the objective function is equivalent to \(-W \log_2 \left( \frac{1-P\alpha^2 \ln \left( 1 - (1-\varepsilon_{max})^{1/N_t} \right)}{\rho PN_t} \right) - q^*(P_0 + P)\) by exploiting the properties of fractional programming, where \( q^* \) is the secrecy energy efficiency when \( P \) is equal to the optimal power \( P^* \) of \( J_1 \), namely

\[
q^* = -W \log_2 \left( \frac{1-P\alpha^2 \ln \left( 1 - (1-\varepsilon_{max})^{1/N_t} \right)}{\rho PN_t \left( P_0 + P^* \right)} \right).
\]

Thus, \( J_1 \) is transformed
\[ J_2 : \min W \log_2 \left( \frac{1 - P \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho P N_t} \right) \]
\[ + q^*(P_0 + P) \]  
\[ \text{s.t.} \]
\[ P \geq \frac{\alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho N_t 2^{-R_{\text{min}}/W}} + \frac{1}{\rho P N_t} \]  
\[ = P_{\text{min}} \]  
\[ P \leq P_{\text{max}}. \]  

\[ J_2, \text{ as a convex optimization problem, can be solved by} \]
\[ \text{the Lagrange multiplier method. By some arrangement, its} \]
\[ \text{Lagrangian dual function can be written as} \]
\[ \mathcal{L}(\mu, \nu, P) = W \log_2 \left( \frac{1 - P \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho P N_t} \right) \]
\[ + q^*(P_0 + P) - \mu P + \mu P_{\text{min}} + \nu P - \nu P_{\text{max}}, \]  

where \( \mu \geq 0 \) and \( \nu \geq 0 \) are the Lagrange multipliers corresponding to the constraint (17) and (18), respectively. Therefore, the dual problem of \( J_2 \) is given by
\[ \max_{\mu, \nu} \min_P \mathcal{L}(\mu, \nu, P). \]  

Given \( \mu \) and \( \nu \), the optimal power \( P^* \) can be derived by solving the following KKT condition
\[ \frac{\partial \mathcal{L}(\mu, \nu, P)}{\partial P} = \frac{W}{\ln 2(\rho^2 \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right) - P)} - q^* - \mu + \nu = 0. \]  

Moreover, \( \mu \) and \( \nu \) can be updated by the gradient method, which are given by
\[ \mu(n + 1) = [\mu(n) - \Delta \mu(P_{\text{min}} - P)]^{+} \]  
\[ \nu(n + 1) = [\nu(n) - \Delta \nu(P - P_{\text{max}})]^{+}, \]  

where \( n \) is the iteration index, and \( \Delta \mu \) and \( \Delta \nu \) are the positive iteration steps. Inspired by the Dinkelbach method [18], we propose an iterative algorithm as follows

Algorithm 1: Energy-Efficient Power Allocation

1. Initialization: Given \( N_t, N_r, W, \alpha, \rho, R_{\text{min}}, P_0, P_{\text{max}}, \Delta \mu, \Delta \nu \) and \( \varepsilon_{\text{max}} \). Let \( \mu = 0, \nu = 0, P = 0 \) and \( q^* = -W \log_2 \left( \frac{1 - P \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho P N_t} \right) / (P_0 + P) \).

2. Update \( \mu \) and \( \nu \) according to (22) and (23), respectively.

3. Computing the optimal \( P^* \) by solving the equation (21).

4. If \( -W \log_2 \left( \frac{1 - P^* \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho P^* N_t} \right) - q^*(P_0 + P^*) > \epsilon \), then set \( q^* = -W \log_2 \left( \frac{1 - P^* \alpha^2 \ln \left( 1 - (1 - \varepsilon_{\text{max}})^{1/N_r} \right)}{\rho P^* N_t} \right) / (P_0 + P^*) \), and go to 2. Otherwise, \( P^* \) is the optimal transmit power.

IV. Numerical Results

To examine the effectiveness of the proposed energy-efficient power allocation scheme, we present several numerical results in the following scenarios: we set \( N_t = 20, N_r = 2, W = 1\, \text{MHz}, R_{\text{min}} = 1.5\, \text{Mbps}, P_0 = 0.5\, \text{Watt} \) and \( P_{\text{max}} = 10\, \text{Watt} \). It is found that the proposed energy-efficient power allocation scheme converges after no more than 20 times iterative computation in all simulation scenarios.

Fig. 2 compares the secrecy energy efficiency of the proposed energy-efficient and the fixed power allocation schemes with \( \varepsilon_{\text{max}} = 0.05, \rho = 0.8 \) and \( N_t = 20 \). Note that we set \( P = P_{\text{max}} \) fixedly for the fixed scheme. As seen in Fig. 2, the proposed scheme performs better than the fixed one, especially when \( \alpha \) is small. For example, when \( \alpha = 1 \), there is about 1.3MB/ gain. It is worth pointing out that our proposed scheme uses less power than the fixed scheme. Therefore, the proposed scheme is more suitable for the future green and secure communications.

Fig. 3 investigates the effect of the outage probability requirements on the secrecy energy efficiency of the proposed scheme with \( \rho = 0.8\) and \( N_t = 20 \). For a given \( \alpha \), as \( \varepsilon_{\text{max}} \) decreases, the secrecy energy efficiency reduces accordingly, this is because more power is used to decrease the outage probability. On the other hand, for a given outage probability requirement, the increase of \( \alpha \) leads to the decrease of the secrecy energy efficiency, since the eavesdropper has a strong eavesdropping ability. It is found that when \( \alpha = 1.4 \) and \( \varepsilon_{\text{max}} = 0.01 \), the secrecy energy efficiency reduces to zero. This is because there is no nonzero secrecy outage capacity under such conditions. Such a challenging problem can be easily solved in LS-MIMO systems by adding the antennas at the BS. As seen in Fig. 4 with the increase of the number of antennas, the secrecy energy efficiency increases significantly, especially when \( \alpha \) is large. Thus, a secure, reliable and QoS guaranteed communication can be realized even with short-distance interception.

Then, we show the impact of the number of antennas at the
eavesdropper on the secrecy energy efficiency of the proposed scheme with $\varepsilon_{\text{max}} = 0.05$, $\rho = 0.8$ and $N_r = 20$. As seen in Fig. 5, with the increase of $N_r$, the energy efficiency decreases accordingly, especially in the region of large $\alpha$. At $\alpha = 1.4$, the secrecy energy efficiency with $N_r = 4$ reduces to zero. Fortunately, this problem can be solved by adding the number of antennas at the BS. Hence, the proposed scheme can address the challenge that the eavesdropper has more antennas than the SU.

Finally, we investigate the impact of imperfect CSI on the secrecy energy efficiency of the proposed scheme with $\varepsilon_{\text{max}} = 0.01$ and $N_r = 40$. As shown in Fig. 6 even with slight CSI mismatch, i.e. $\rho = 0.95$, there is performance loss with respect to the ideal case of $\rho = 1$. With the increase of $\rho$, secrecy energy efficiency decreases accordingly.

V. CONCLUSION

In this paper, we show that the large number of antenna elements of LS-MIMO system can address the problem of guaranteeing both stringent security and high QoS requirements when the eavesdropper is closer to the BS and has more antennas than the SU. The impact of imperfect CSI at the BS is investigated quantitatively. We also design an energy-efficient power allocation scheme to enable a secure communication while satisfy the QoS constraint. Our analysis and numerical results show that LS-MIMO is an energy-efficient technique that provides physical layer security even under some adverse conditions.

APPENDIX

By using the transmit beam for MRT $\textbf{w} = \hat{\textbf{h}}/||\hat{\textbf{h}}||$, the legitimate channel capacity can be expressed as

$$C_s = W \log_2 \left( 1 + P \left( \sqrt{\rho} \hat{\textbf{h}} + \sqrt{1 - \rho} \textbf{e} \right)^H \hat{\textbf{h}} \right)$$
\[
\begin{align*}
W \log \left(1 + \rho P \|\hat{h}\|^2 + 2\rho(1 - \rho)P\Re(e^{H}\hat{h}) \right) \\
+ (1 - \rho)P\|e^{H}\|^2/\|\hat{h}\|^2 \right) \\
\approx W \log_2(1 + \rho P \|\hat{h}\|^2) \\
\approx W \log_2(1 + \rho PN_t) \\
\approx W \log_2(\rho PN_t),
\end{align*}
\]

where \(\Re(x)\) denotes the real part of \(x\). \((25)\) follows the fact that \(\rho P \|\hat{h}\|^2\) scales with the order \(O(\rho PN_t)\) as \(N_t \to \infty\) while \(2\rho(1 - \rho)P\Re(e^{H}\hat{h}) + \frac{(1 - \rho)P\|e^{H}\|^2}{\|\hat{h}\|^2}\) scales as the order \(O(1)\), so the third and fourth terms can be negligible. \((26)\) holds true because of \(\lim_{N_t \to \infty} \frac{\|\hat{h}\|^2}{N_t} = 1\), and \((27)\) neglects the constant 1 in the case of large \(N_t\). Therefore, we get the Lemma 1.

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