Optimal Transmit Antenna Selection for Massive MIMO Wiretap Channels

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Abstract—In this paper, we study the impacts of transmit antenna selection on the secrecy performance of massive MIMO systems. We consider a wiretap setting in which a fixed number of transmit antennas are selected and then confidential messages are transmitted over them to a multi-antenna legitimate receiver while being overheard by a multi-antenna eavesdropper. For this setup, we derive an accurate approximation of the instantaneous secrecy rate. Using this approximation, it is shown that in some wiretap settings under antenna selection the growth in the number of active antennas enhances the secrecy performance of the system up to some optimal number and degrades it when this optimal number is surpassed. This observation demonstrates that antenna selection in some massive MIMO settings not only reduces the RF-complexity, but also enhances the secrecy performance. We then consider various scenarios and derive the optimal number of active antennas analytically using our large-system approximation. Numerical investigations show an accurate match between simulations and the analytic results.

Index Terms—Massive MIMO wiretap channel, physical layer security, transmit antenna selection.

I. INTRODUCTION

Over the past few years, the popularity of smart phones, electronic tablets and video streaming as well as the sharp rise in the number of service providers has led to an explosive growth of data traffic in wireless networks. This increasing demand of capacity in mobile broadband communications poses challenges for designing the next generation of cellular networks (5G) in the near future [2]. Given this backdrop, confidential and private transmission of data in the next generation of wireless networks is of paramount importance. In this respect, physical layer security for 5G wireless networks has gained significant attentions in recent years aiming for design of reliable and secure transmission schemes [3], [4]. Unlike the traditional approaches relying on cryptographic techniques [5], physical layer security provides secrecy by exploiting the inherent characteristics of wireless channels. Although cryptographic techniques employed in the upper layers of networks protect processed data securely, physical layer security is a potential solution through the communication phase [6].

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The basic model for physical layer security is the wiretap channel in which transmitted messages to a legitimate receiver are being overheard by an eavesdropper. Wyner demonstrated that secrecy is obtained in this setting as long as the legitimate receiver communicates over a channel whose quality is better than the eavesdropper channel [7]. Based on this framework, several techniques such as artificial noise generation [8], [9] and cooperative jamming [10] were proposed for secrecy enhancement. The extension of Wyner’s framework to Multiple-Input Multiple-Output (MIMO) settings has moreover shown a promising performance of such settings in the presence of eavesdroppers [11]–[13]. In fact, in MIMO wiretap channels, also referred to as Multiple-Input Multiple-Output Multiple-Eavesdropper (MIMOME) channels, the Base Station (BS) can focus its main transmit beam to the legitimate terminals, and thus, reduce the information leakage to the eavesdroppers. This technique in massive MIMO settings [14] asymptotically cancels out passive malicious terminals in the network making these settings robust against passive eavesdropping [15].

Despite promising characteristics of massive MIMO systems, they are known to pose high Radio Frequency (RF)-cost and complexity. In fact, employing a separate RF chain per antenna in massive MIMO systems imposes a burden from the implementational point of view [16]. This issue has introduced the antenna selection [17] along with other approaches such as spatial modulation [18] and hybrid analog-digital precoding schemes [19], [20] as prevalent strategies in massive MIMO. In antenna selection, only a subset of antennas is set to be active in each coherence time. This subset is in general selected with respect to some performance metric such as achievable transmission rate, outage probability or bit error rate [17]. The optimal approaches to antenna selection however deal with an exhaustive search which is not computationally feasible in practice. Alternatively, several suboptimal, but complexity efficient, methods have been proposed in the literature; see for example the approaches in [21]–[24]. The investigations have shown that these suboptimal approaches do not impose a significant loss on the performance for several MIMO settings [23], [25], [26]. In the context of massive MIMO systems, recent studies have demonstrated that the large-system properties of these systems are maintained even via simple antenna selection algorithms [27], [28].

In addition to implementational complexity reduction, antenna selection was also observed to be beneficial in MIMO systems with respect to some performance measures such as secrecy rate [29], [30], energy efficiency [31] and effective rate [32] in some special cases. For instance, it was shown in...
that single Transmit Antenna Selection (TAS), i.e., only one transmit antenna being active, in a conventional MIMO setup can achieve high levels of security, especially when the total number of transmit antennas increases. The study was later extended in [34] to cases with multi-antenna eavesdroppers demonstrating that similar results hold also in these settings. In [35], secure transmission in a general MIMOME channel was investigated under single TAS. Such results were further extended in the literature for other MIMO settings. For example in [36], secure transmission was studied for Nakagami-$m$ fading channels under single TAS. The impacts of imperfect channel estimation and antenna correlation were also investigated in [37]. The average secrecy rate and secrecy diversity analysis for a simple single TAS scheme was moreover studied in [38], [39]. In [40], TAS with outdated Channel State Information (CSI) was analyzed for scenarios with single-antenna receivers. The effect of single TAS at the BS in the presence of randomly located eavesdroppers with a full-duplex receiver was moreover studied in [41]. In contrast to single TAS, the secrecy performance of MIMOME channels under the multiple TAS, i.e., setting multiple transmit antennas to be active, has not yet been addressed in the literature. In fact under multiple TAS, the growth in the number of transmit antennas is beneficial to both the legitimate receiver and the eavesdropper, and therefore, its effect on the overall secrecy performance is not clear. This paper intends to study the impact of multiple TAS in massive MIMO settings.

Contributions and Organization

We study the secrecy performance of a MIMOME channel in which the BS employs a computationally simple TAS algorithm to select a fixed number of transmit antennas. For this setting, the distribution of the instantaneous secrecy rate in the large-system limit, i.e., when the number of transmit antennas grows large, is accurately approximated. This approximation is then utilized to investigate the secrecy performance in two different scenarios: Scenario (A) in which the eavesdropper’s CSI is available at transmit side, and Scenario (B) in which the BS does not know the eavesdropper’s CSI. Our investigations demonstrate that in both scenarios, there exist cases in which the secrecy performance is optimized when the number of active antennas is less than the total number of transmit antennas. In other words, the growth in the number of selected antennas in some cases enhances the secrecy performance up to an optimal value; however, it becomes destructive if the number of the active antennas surpasses this optimal value. Invoking our large-system results, we develop a framework to derive analytically this optimal value. The consistency of our approach is then confirmed through numerical investigations.

The remaining parts of this manuscript is structured as follows: Section II describes the system model. In Section III we conduct analyses for large dimensions. The impacts of TAS on the secrecy performance is investigated in Section IV where we also give some numerical results and discussions. Finally, the concluding remarks are given in Section V. The proofs of the main theorems are moreover provided in the appendices.

Notations: Throughout the paper, scalars, vectors and matrices are denoted by non-bold, bold lower case, and bold upper case letters, respectively. $\mathbb{C}$ represents the complex plain. The Hermitian of $H$ is indicated with $H^H$, and $I_N$ is the $N \times N$ identity matrix. The determinant of $H$ and Euclidean norm of $x$ are shown by $|H|$ and $\|x\|$, respectively. $\lfloor x \rfloor$ refers to the integer with minimum Euclidean distance from $x$. The binary and natural logarithm are denoted by $\log(\cdot)$ and $\ln(\cdot)$, respectively, and $1_{\{\cdot\}}$ represents the indicator function. $\mathbb{E}\{\cdot\}$ is the mathematical expectation, and $Q(x)$ and $\phi(x)$ denote the standard Q-function and the zero-mean and unit-variance Gaussian distribution, respectively.

II. Problem Formulation

We consider a Gaussian MIMOME wiretap setting in which the transmitter, the legitimate receiver and the eavesdropper are equipped with multiple antennas represented by $M$, $N_r$, and $N_e$, respectively. The main channel, from the transmitter to the legitimate receiver, and the eavesdropper channel, from the transmitter to the eavesdropper, are assumed to be statistically independent and experience quasi-static Rayleigh fading. The CSI of the both channels is considered to be available at the receiving terminals. The transmitter is moreover assumed to know the CSI of the main channel. In practice, the CSI is obtained at the respective terminals by performing channel estimation which depends on the duplexing mode of the system. Massive MIMO settings are usually considered to operate in the time division duplexing mode in which it is sufficient to estimate the channel only in the uplink training mode due to the channel reciprocity. More details on channel estimation in massive MIMO settings are found in [42] Chapter 3. Based on the availability of the eavesdropper’s CSI at the transmitter, we consider two different scenarios in this paper:

(A) The eavesdropper’s CSI is available at the transmitter.

(B) The transmitter does not know the eavesdropper’s CSI.

A. System Model

The encoded message $x_{M \times 1}$ is transmitted over the main channel. In this case, the received signal $y_{N_r \times 1}$ reads

$$y = \sqrt{\rho_m} H_m x + n_m$$

(1)

where $H_m \in \mathbb{C}^{N_r \times M}$ represents the main channel matrix, $\rho_m$ denotes the average Signal-to-Noise Ratio (SNR) at each receive antenna and $n_m$ is zero-mean and unit-variance complex Gaussian noise, i.e., $n_m \sim \mathcal{CN}(0, I_{N_r})$. Since the channel is assumed to be quasi-static Rayleigh fading, the coherence time is significantly larger than the transmission interval and entries of $H_m$ are modeled as independent and identically distributed (i.i.d.) complex-valued Gaussian random variables with zero-mean and unit-variance.

At the eavesdropper, $x$ is overheard and the signal

$$z = \sqrt{\rho_e} H_e x + n_e$$

(2)

is received where $H_e \in \mathbb{C}^{N_e \times M}$ is the eavesdropper channel matrix enclosing the fading coefficients between the transmit and eavesdropper’s antennas. The entries if $H_e$ are modeled as i.i.d. complex-valued Gaussian random variables with zero-mean and unit-variance, since the channel experiences quasi-static Rayleigh fading. $n_e \sim \mathcal{CN}(0, I_{N_e})$ represents additive

white Gaussian noise at the eavesdropper and $\rho_e$ denotes the average SNR at each of the eavesdropper’s antennas. While both the receiving terminals utilize all their available antennas, the transmitter employs the TAS protocol $S$ to select a subset of its antennas. The protocol is illustrated in the following.

**TAS Protocol:** Let $h_{e,m} \in \mathbb{C}^{N_e}$ represent the $l$-th column vector of $H_m$ and $L$ be the number of transmit antennas desired to be selected. Denote the index set of columns sorted with respect to their magnitudes by $\mathcal{W} := \{w_1, \ldots, w_M\}$ such that

$$\|h_{w_1,m}\| \geq \|h_{w_2,m}\| \geq \cdots \geq \|h_{w_M,m}\|. \quad (3)$$

The TAS protocol $S$ selects $L$ antennas which correspond to the first $L$ indices in $\mathcal{W}$, i.e., $\mathcal{W}_S := \{w_1, \ldots, w_L\}$.

Corresponding to the TAS protocol, the effective main and eavesdropper channel, namely $H_m$ and $H_e$, are respectively constructed from $H_m$ and $H_e$ by collecting those column vectors which correspond to the selected antennas. For instance, $H_m$ is an $N_t \times L$ matrix with columns $h_{w_1,m}, \ldots, h_{w_L,m}$. Note that although the TAS protocol $S$ selects the strongest antennas corresponding to the main channels, it performs as a random TAS protocol for the eavesdropper, since $H_m$ and $H_e$ are statistically independent.

**Remark:** In practice, $\mathcal{W}_S$ in the TAS protocol can be determined either by employing a rate-limited feedback channel from the legitimate receiver to the BS or by estimating the CSI at the BS. One may note that in the former case, the rate-limited channel requires a low overhead. Moreover, in the latter case, the transmitter need not to acquire the complete CSI. In fact, as $\mathcal{W}_S$ is determined via the ordering in $\mathcal{W}$, the transmitter only needs to estimate the channel norms. This task can be done at the prior uplink stage simply by analog power estimators, and requires a significantly reduced time interval compared to the case of complete CSI estimation. This reduced interval furthermore allows for averaging over the coherence time which can improve the power estimation; see [43] for more details.

### B. Achievable Secrecy Rate

For the MIMOME wiretap setting specified by $H_m$ and $H_e$, the instantaneous achievable secrecy rate reads [12]

$$R_s = [R_m - R_e]^+ \quad (4)$$

where $[x]^+ = \max\{0, x\}$. In [4], $R_m$ denotes the achievable rate over the main channel which reads

$$R_m = \log|I + \rho_m H_m Q_m H_m^H| \quad (5)$$

and $R_e$ is the achievable rate over the eavesdropper channel which is given by

$$R_e = \log|I + \rho_e H_e Q_e H_e^H| \quad (6)$$

with $Q_{M \times M}$ being the power control matrix. For simplicity, we assume uniform power allocation over active antennas with unit average transmit power on each antenna. This means that

$$[Q]_{ww} = \begin{cases} 1 & w \in \mathcal{W}_S \\ 0 & w \notin \mathcal{W}_S \end{cases} \quad (7)$$

Consequently, the instantaneous rates $R_m$ and $R_e$ reduce to

$$R_m = \log|I + \rho_m H_m H_m^H| \quad (8a)$$

$$R_e = \log|I + \rho_e H_e H_e^H|. \quad (8b)$$

Note that $R_e$ in (8b) is determined under the worst-case scenario in which the eavesdropper knows the indices of antennas selected by the protocol $S$. Substituting into (4), the maximum achievable instantaneous secrecy rate reads

$$R_s(S) = \left[ \log \frac{|I + \rho_m H_m H_m^H|}{|I + \rho_e H_e H_e^H|} \right]^+ \quad (9)$$

where the argument $S$ is written to indicate the dependency of the achievable secrecy rate on the TAS protocol. Note that when the eavesdropping terminal is not capable of obtaining the indices of the selected antennas, (9) bounds the achievable instantaneous secrecy rate from below. Since the channels experience fading, $R_s(S)$ is a random variable whose statistics define different secrecy performance metrics, e.g., the ergodic secrecy rate and secrecy outage probability. In the sequel, we evaluate the asymptotic distribution of $R_s(S)$.

### III. Large-System Secrecy Performance

The secrecy performances in Scenarios A and B are quantified via different metrics. In Scenario A, since the BS knows the eavesdropper’s CSI, it transmits with rate $R_s(S)$ in each coherence time; thus, the secrecy performance is measured by the achievable ergodic secrecy rate. When the eavesdropper’s CSI is not available at the BS, the transmitter assumes the secrecy rate to be $R_s$. In this case, the secure transmission is guaranteed as long as $R_m - R_e > R_s$. Consequently, in Scenario B, the secrecy performance is properly quantified by the secrecy outage capacity; see [44] for further discussions.

Based on above discussions, the performance of the setting in both Scenarios A and B is described by statistics of $R_s(S)$. We hence derive an accurate large-system approximation for the distribution of $R_s(S)$ in Theorem 1. Here by the large-system limit we mean $M \uparrow \infty$. To state Theorem 1, we define the “asymmetrically asymptotic regime of eavesdropping”.

**Definition 1** (asymmetrically asymptotic regime of eavesdropping): The eavesdropper is said to overhear in the asymmetrically asymptotic regime of eavesdropping when the number of eavesdropper’s antennas per active antenna, defined as $\beta_e := N_e/L$, reads either $\beta_e \ll 1$ or $\beta_e \gg 1$.

In Definition 1 $\beta_e \ll 1$ describes scenarios in which the eavesdropper is a regular mobile terminal with finite number of antennas. Moreover, $\beta_e \gg 1$ represents MIMOME settings with sophisticated eavesdropping terminals such as portable stations in cellular networks. In the sequel, we assume that the understudy setting operates in the asymmetrically asymptotic regime of eavesdropping. However, our numerical investigations later depict that the results are valid even when the system does not operate in this regime of eavesdropping.
Theorem 1: Consider the TAS protocol \( \mathcal{S} \), and let
\[
\eta_t = N_t [L + M f_{N_t+1}(u)]
\]
\[
\sigma_t^2 = (uL - \eta_t)^2 \left( \frac{1}{L} - \frac{1}{M} \right) - \frac{\eta_t^2}{L} + \Xi_t
\]
for some non-negative real \( u \) which satisfies
\[
\int_u^\infty f_N(x)dx = \frac{L}{M}.
\]
\( \Xi_t \) which is given by
\[
\Xi_t := N_t (N_t + 1) [L + M f_{N_t+1}(u) + M f_{N_t+2}(u)],
\]
and \( f_{N_t}(\cdot) \) which represents the chi-square probability density function with \( 2N_t \) degrees of freedom and mean \( N_t \), i.e.,
\[
f_N(x) = \frac{1}{(N_t - 1)!} \left\{ x^{N_t-1} e^{-x}, \quad \text{if } x \geq 0 \right\}
\]
\[
= 0, \quad \text{if } x < 0.
\]
Define the integers \( U_m := \min \{ L, N_t \}, V_m := \max \{ L, N_t \} \), \( U_e := \min \{ L, N_e \} \) and \( V_e := \max \{ L, N_e \} \) and assume that the eavesdropper overhears in the asymmetrically asymptotic regime of eavesdropping. Then, as \( M \) grows large, the distribution of the instantaneous secrecy rate \( R_e(S) \) is effectively approximated by the distribution of \( R_{\text{asy}}(S) := [R^*]^+ \) where \( R^* \) is Gaussian with mean \( \eta \) and variance \( \sigma^2 \) given by
\[
\eta := U_m \log \left( \frac{K_t}{U_m} \right) - C_t \psi \rho_m \eta_t - U_e \log (1 + \rho_e V_e), \quad (14a)
\]
\[
\sigma^2 := \left[ \left( 1 - \frac{C_t}{K_t} \right) \frac{U_m \rho_m \sigma_t}{K_t} \right]^2 + \frac{U_e V_e \rho_e^2}{(1 + \rho_e V_e)^2} \psi^2 \quad (14b)
\]
for \( K_t := U_m + \rho_m \eta_t \) and \( C_t := \rho_m \eta_t U_m (U_m - 1) / V_m \) and the constant \( \psi = \log e = 1.4427 \).

Proof: The proof follows the hardening property of the main and eavesdropper channel. In fact, the results of [23] indicate that in the large-system limit, \( R_m \) is approximately Gaussian with a vanishing variance. The eavesdropper channel is moreover shown to harden in an asymmetrically asymptotic regime of eavesdropping following the discussions in [45]. The detailed derivations are given in Appendix A.

From (14b), one observes that the variance of the secrecy rate vanishes in the large-system limit. In fact, as \( M \) grows large, \( \eta_t \) increases, and hence, the first term in (14b) tends to zero. Moreover, in the asymmetrically asymptotic regime of eavesdropping, \( U_e / V_e \) is significantly small and the two other terms are negligible. Consequently, in the large-system limit \( \sigma \) converges to zero. This observation could be intuitively predicted, due to the fact that the both channels harden asymptotically. The mean value \( \eta \), however, does not necessarily increase as \( M \) grows, since it is given as the difference of two terms which can both asymptotically grow large. The latter observation indicates that increasing the number of selected antennas for this setup does not necessarily improve the secrecy rate. We discuss this argument later in Section IV.

At this point, we employ Theorem [1] to investigate the secrecy performance of the system in Scenarios A and B.

Remark: Theorem [1] gives a “large-system approximation”. This means that for fixed \( L, N_t \) and \( N_e \), \( R_{\text{asy}}(S) \) accurately approximates the statistics of the instantaneous secrecy rate when \( M \) is large enough. Note that the theorem does not impose any constraint on the growth of \( L, N_t \) and \( N_e \), and the approximation is valid as long as the assumptions of the theorem are fulfilled. Nevertheless, our numerical investigations show that even for \( M = 16 \), which is not so large, this approximation is highly accurate.

A. Secrecy Performance in Scenario A

When the BS knows the eavesdropper’s CSI, the instantaneous secrecy rate is achievable in each transmission interval. Assuming that the symbols of the given codeword observe different realizations of the channel, the maximum average rate achieved by the transmitter is determined by the expectation of the instantaneous secrecy rate. This average rate is referred to as the achievable ergodic secrecy rate and is considered as an effective performance metric in this case. Using Theorem [1] the achievable ergodic secrecy rate \( R_{\text{Erg}}(S) \) for our setup in the large-system limit is approximated as
\[
R_{\text{Erg}}(S) \approx \mathbb{E} \left\{ R_{\text{asy}}(S) \right\} = \mathbb{E} \left\{ [R^*]^+ \right\} = \sigma \phi (\xi) + \eta Q(-\xi). \quad (15)
\]
where \( \xi := \eta / \sigma \). Using the inequality \( Q(x) < \phi (x) / x \) for \( x > 0 \) and the fact that \( Q(-x) + Q(x) = 1 \), we can bound the ergodic secrecy rate as
\[
R_{\text{Erg}}(S) > \eta \quad (16)
\]
for \( \xi > 0 \). By numerical investigations, it is seen that the lower bound is tight when \( \xi \) is large enough. Fig. 1 illustrates the accuracy of the approximations, as well as the tightness of the bound. The figure has been plotted for \( L = 8 \) and \( M = 16 \) transmit antennas which is practically small. The SNR at
the eavesdropping terminal is considered to be \( \log \rho_e = -5 \, \text{dB} \) and the receiving terminals have been assumed to have \( N_t = N_e = 2 \) antennas. As the figure shows, the approximation is consistent with the simulations within a large range of SNRs. The lower bound in (16) moreover perfectly matches \( \mathcal{R}_{\text{Erg}}(S) \) except for the interval of \( \rho_m \) in which \( \eta \) is close to zero. This observation is due to the fact that the variance in the large-system limit tends to zero rapidly, and thus, \( \xi = \eta/\sigma \) grows significantly large even for finite values of \( \eta \). Consequently, one can write \( Q(-\xi) \approx 1 - \phi(\xi)/\xi \) and approximate the achievable ergodic rate with \( \eta \) accurately. Although the approximation in Theorem 1 is given for the large-system limit and asymmetrically asymptotic regime of eavesdropping, one observes that the result is accurately consistent with the simulations even for not so large dimensions and \( \beta_o = 1/8 \).

B. Secrecy Performance in Scenario B

In Scenario B, the eavesdropper’s CSI is not known at the BS. This means that for a given realization of the channels, the instantaneous secrecy rate in (4) cannot be achieved. This is due to the fact that the transmitter achieves the secrecy rate in (4) by constructing its codewords based on the leakage rate achievable over the eavesdropper channel. For this scenario, the \( \epsilon \)-outage secrecy rate is known to be the proper metric quantifying the secrecy performance. Considering a given rate \( R_o \geq 0 \) the secrecy outage probability \( \mathcal{P}_{\text{Out}}(R_o) \) is defined as the maximum possible rate for which \( \mathcal{P}_{\text{Out}}(R_o) \leq \epsilon \). The intuition behind defining the \( \epsilon \)-outage secrecy rate as the performance metric can be stated as the following: Since the BS does not know the CSI of the eavesdropper channel, it assumes that the achievable secrecy rate is at least \( R_o \) in all transmission intervals. Noting that the CSI of the main channel is known at the BS, the setting of the secrecy rate implicitly imposes this assumption on the quality of the eavesdropper channel that \( R_e < R_m - R_o \) in which the term \( R_m - R_o \) is known by the transmitter. Consequently, the secrecy outage probability in (17) determines the probability of the eavesdropper having better channel quality than the assumed term \( R_m - R_o \), or equivalently, the fraction of intervals in which the eavesdropper can decode transmit codewords at least partially. As a result, \( \mathcal{R}_{\text{Out}}(\epsilon) \) determines the maximum achievable secrecy rate for which one can guarantee that the fraction of transmission intervals with information being leaked to the eavesdropper is less than \( \epsilon \).

From Theorem 1 the outage probability is approximated as

\[
\mathcal{P}_{\text{Out}}(R_o) \approx \Pr \{ R_{\text{asy}}(S) \leq R_o \} = \Pr \{ R^* \leq R_o \} = 1 - Q\left( \frac{R_o - \eta}{\sigma} \right). \tag{18}
\]

Consequently, the \( \epsilon \)-outage secrecy rate is given by

\[
\mathcal{R}_{\text{Out}}(\epsilon) = \sigma Q^{-1}(1 - \epsilon) + \eta \tag{19}.
\]

with \( Q^{-1}(\cdot) \) being the inverse of the Q-function with respect to composition. Moreover, the probability of non-zero secrecy rate \( \mathcal{P}_{\text{NZS}}, \) defined as \( \mathcal{P}_{\text{NZS}} := \Pr \{ \mathcal{R}_e(S) > 0 \} \), in the large-system limit is approximated as \( \mathcal{P}_{\text{NZS}} \approx 1 - Q(\eta/\sigma) \).

Fig. 2 shows the secrecy outage probability as a function of \( \rho_m \) for \( R_o = 5 \) considering various values of \( N_t \) and \( L \). Here, \( N_e = 8 \) and \( \log \rho_e = -10 \, \text{dB} \) and the BS is considered to be equipped with \( M = 128 \) antennas. As it is seen, the large-system approximation consistently tracks the numerical result for a large range of SNRs. Although Theorem 1 approximates the distribution of the instantaneous secrecy rate in the asymmetrically asymptotic regime of eavesdropping, one can see that the results closely match the simulations even for \( \beta_e = 1 \).

IV. Secrecy Enhancement via TAS

In this section, we investigate the impacts of TAS on the secrecy performance in both Scenarios A and B. Let us start with Scenario A. As it was discussed, the secrecy performance in this case is characterized by the ergodic secrecy rate whose large-system approximation is given in Section III-A. Considering the ergodic secrecy rate \( \mathcal{R}_{\text{Erg}}(S) \) as a function of \( L \), one observes that for different choices of \( \rho_e, \rho_m, N_t \) and \( N_e \), the ergodic secrecy rate may strictly increase with \( L \) within the interval \( \{1, \ldots, M\} \) or have a maxima at some integer \( L^* < M \). This observation suggests that for the considered setting the secrecy performance can be enhanced in some cases via TAS. Fig. 3 illustrates this point. In this figure, the ergodic secrecy rate is plotted as a function of \( L \), for several realizations of the setting with \( M = 128 \) considering both the large-system approximation and numerical simulations. The SNRs at the legitimate receiver and eavesdropper are set to \( \log \rho_m = 0 \, \text{dB} \) and \( \log \rho_e = -10 \, \text{dB} \), respectively. As the figure shows, the ergodic secrecy rate in some curves meets its maximum at some values of \( L \) which is significantly smaller than \( M \). This observation depicts that TAS in these scenarios, not only benefits in terms of RF-cost and complexity, but also enhances the secrecy performance of the system. The intuition
behind this behavior comes from the fact that the growth in the number of selected antennas improves the quality of the both channels. For some cases, including those shown in Fig. 3, the improvement from the eavesdropper’s point of view dominates the overall growth in the secrecy rate, if a certain number of active antennas is surpassed. This means that by setting \( L \) to be more than this given number, the quality improvement at the eavesdropping terminal starts to exceed the enhancement at the legitimate receiver. Considering Scenario B, similar behavior can be observed in terms of \( \epsilon \)-outage secrecy rate \( R_{\text{Out}}(\epsilon) \). In Fig. 4 the \( \epsilon \)-outage secrecy rate for \( \epsilon = 0.01 \) has been plotted in terms of \( L \) for several examples considering \( M = 128 \), \( \log \rho_m = 0 \) dB and \( \log \rho_e = -10 \) dB.

\[ \text{Definition 2 (Prevalence Set): Let } \mathcal{M}(L) \text{ denote the secrecy performance metric for } L \text{ active transmit antennas. The legitimate receiver is said to be relatively prevailing if } \mathcal{M}(L) \text{ is a monotonically increasing function of } L. \text{ Moreover, the set of all tuples } (\rho_m, \rho_e, N_t, N_e) \text{ for which the legitimate receiver is relatively prevailing is referred to as the prevalence set for the legitimate receiver represented by } \mathcal{S}_R. \text{ Similarly, the eavesdropper is said to be relatively prevailing if } \min \left\{ \arg \max_{L \in \{1, \ldots, M\}} \mathcal{M}(L) \right\} < M. \]  

\[ (20) \]

B. Sufficient Conditions for Prevalence

Using the large-system approximation, one can determine \( \mathcal{S}_R \) and \( \mathcal{S}_E \) for large \( M \) analytically. The result is however of a complicated form in general. Alternatively, one may derive a set of sufficient conditions for which the prevalence of the legitimate or eavesdropping terminal is guaranteed. \textbf{Theorem 2} gives a set of sufficient conditions for the legitimate receiver to be relatively prevailing.

\textbf{Theorem 2:} Let the transmitter be equipped with \( M \) transmit antennas and assume the asymmetrically asymptotic regime of eavesdropping. For a given tuple \( T = (\rho_m, \rho_e, N_t, N_e) \), define the fixed-point function \( f(\cdot|T) \) to be

\[ f(\ell|T) := F(\ell) + f_R(\ell|\rho_m, N_t) - f_E(\ell|\rho_e, N_e) \]  

\[ (21) \]

where the function \( F(\ell) \) reads

\[ F(\ell) = \frac{\rho_m u U_m}{U_m + \rho_m \eta_t} \left( 1 + 2 \Lambda(\ell) \frac{U_m(U_m - 1)}{\rho_m \eta_t V_m} \right) \]  

\[ (22) \]

with \( u \) and \( \eta_t \) being defined in \textbf{Theorem 1}, \( U_m = \min \{ \ell, N_t \} \), \( V_m = \max \{ \ell, N_t \} \) and

\[ \Lambda(\ell) = \frac{\psi}{2} \left( \frac{\rho_m \eta_t}{U_m + \rho_m \eta_t} \right)^2. \]  

\[ (23) \]
Moreover, $f_R(\ell | \rho_m, N_c)$ and $f_E(\ell | \rho_e, N_c)$ are given by (25a) and (25b) on the top of the next page with $E(\ell)$ reading
\[
E(\ell) = 1 - \frac{U_m}{U_m + \rho_m \eta} \left[ 1 - \Lambda(\ell) \frac{U_m + (2U_m - 1) \rho_m \eta}{U_m V_m} \right].
\] (24)

Then, the legitimate receiver is relatively prevailing in both Scenarios A and B if $f(\ell | T) > 0$ for all real $\ell \in [1, M]$.

**Proof:** The proof follows by bounding the first derivatives of the large-system approximations for the ergodic and e-outage secrecy rate by a similar term, and is given in Appendix D.

Theorem 2 intuitively indicates that the legitimate receiver is prevailing when the growth in the achievable rate over the main channel by increasing the number of active antennas always dominates the growth over the eavesdropper channel. In fact, the first two terms in the right hand side of (21) bound the rate growth over the main channel while $f_E(\ell | \rho_e, N_c)$ describes the improvement in the quality of the eavesdropper channel in the large-system limit. Using Theorem 2 one can discuss whether secrecy enhancement is achievable in the setting via TAS or not. One should note that this theorem states only a sufficient condition. This means that there exist tuples which do not fulfill the conditions given in Theorem 2 and still are optimal under full complexity in the sense of secrecy performance. For these cases, one may further study necessary conditions. In the following, we study some examples.

**Example 1:** Consider the following two scenarios:

(a) The legitimate and eavesdropping terminals are equipped with $N_t = 8$ and $N_e = 2$ antennas, respectively and we have $\log \rho_m = 0 \text{ dB}, \log \rho_e = -10 \text{ dB}$ and $M = 128$.

(b) The eavesdropper is equipped with a single antenna while $N_t > 1$. The number of transmit antennas unboundedly grows large, i.e., $M \uparrow \infty$.

From Theorem 2 one can show that for the setting in (a) the sufficient conditions are satisfied, and thus, the legitimate receiver is relatively prevailing in both Scenarios A and B. This result agrees with this intuition that the legitimate receiver is prevailing, since both the number of receive antennas and the SNR are relatively better at the this terminal.

For (b), we invoke Theorem 2 and derive a set of conditions under which the legitimate receiver becomes relatively prevailing. Since $M \uparrow \infty$, one can show that for this case $\Lambda(\ell) \approx \psi/2$ and $E(\ell) \approx 1$. Moreover, the function $F(\ell)$ in the large-system limit can be approximated as
\[
F(\ell) \approx \frac{u U_m}{N_t \ell + N_t M f_{N_t+1}(u)}
\] (26)
with $u$ and $f_{N_t+1}(u)$ given in Theorem 1. Substituting in (21), the constraints in (27) at the top of the next page is derived. When $M \uparrow \infty$, one concludes that $N_t \geq 1 + \sqrt{2M}$ is sufficient for the prevalence of the legitimate receiver. Note that this constraint does not depend on the SNRs. For instance, considering $M = 128$, a legitimate terminal with $N_t = 17$ antennas is relatively prevailing for any choice of $\rho_m$ and $\rho_e$. Fig. 5 shows the achievable ergodic rate for $M = 128$, $N_c = 1$ and $N_t = 17$ considering several choices of $\rho_e$ and $\rho_m$. As the figure depicts, the optimal choice for $L$ in all the cases is $L^* = M$ which agrees with the analytic result.

**V. OPTIMAL NUMBER OF ACTIVE ANTENNAS**

When the eavesdropper is relatively prevailing, the secrecy performance metric is maximized by choosing the number of active antennas optimally. We investigate this problem through some examples considering both Scenarios A and B.

**A. Scenario A**

The large-system approximation of $R_{Erg}(S)$ in (15) is a function of $L$ whose maxima occurs at some $L^* \in [1 : M]$ when the eavesdropper is relatively prevailing. We derive this maxima analytically for some examples in the sequel.

**Example 2** (Single-antenna receivers): Consider the scenario in which the receiving terminals are equipped with a single antenna, i.e., $N_t = N_e = 1$. Assume that the eavesdropper’s CSI is available at the transmitter.

We intend to derive the optimal number of active antennas $L^*$ which maximizes $R_{Erg}(S)$. To do so, we initially assume that with $L^*$ active transmit antennas the setting performs in the asymmetrically asymptotic regime of eavesdropping, i.e., $L^* \gg 1$. We later show that this prior assumption is true. By substituting into (14a) and (14b), $\eta$ and $\sigma^2$ are determined as
\[
\eta = \log \left( \frac{1 + \rho_m L (1 + \ln ML^{-1})}{1 + \rho_e L} \right)
\] (28a)
\[
\sigma^2 = \frac{\rho_e^2 L (2 - \eta L^{-1})}{(1 + \rho_e L)^2} + \frac{L \rho_e^2}{(1 + \rho_e L)^2} \psi^2.
\] (28b)

Under the assumption $L^* \gg 1$, the achievable ergodic secrecy rate for $M \uparrow \infty$ is further approximated as $R_{Erg}(S) \approx \eta$. To find $L^*$, we define the function
\[
\mathcal{R}(\ell) := \log \left( \frac{1 + \rho_m \ell + \rho_m \ell \ln ML^{-1}}{1 + \rho_e \ell} \right)
\] (29)
for real $\ell$, $\mathcal{R}(\cdot)$ is the real envelope of the ergodic secrecy rate whose values at integer points give the ergodic secrecy rate for the given number of active antennas. In this case, one can straightforwardly show that for any choice of $\rho_m$ and $\rho_e \neq 0$, there exists some real $\ell \in [1, M]$ for which $\mathcal{R}(\ell) < 0$. This fact indicates that with $N_t = N_e = 1$, the eavesdropper is relatively prevailing as long as $\rho_e \neq 0$, and thus, $L^* < M$. To find $L^*$, one notes that $\mathcal{R}''(\ell) \leq 0$ for $\ell \in [0, M]$, and thus, $L^*$ is the closest integer to the maxima of $\mathcal{R}(\cdot)$. Consequently, the optimal number of active transmit antennas is approximated as $L^* \approx \lceil \ell^* \rceil$ where $\ell^*$ satisfies
\[
\rho_e \ell^* + \ln \ell^* + \frac{\rho_e}{\rho_m} = \ln M.
\] (30)

From (30), one observes that $L^*$ grows with $M$, and therefore, the eavesdropping regime is asymmetrically asymptotic, i.e., the initial assumption $L^* \gg 1$ holds. Moreover, by reducing $\rho_e \downarrow 0$ in (30), $L^* = M$ which agrees with the fact that in the absence of eavesdroppers, the achievable ergodic secrecy rate is a monotonically increasing function of $L$.

\(^1\)Note that $\mathcal{R}(\ell) < 0$ holds for large $\ell$ which agrees with the initial assumption of being in the asymmetrically asymptotic regime of eavesdropping.
In contrast to Example 2, the fixed-point equation in (30), results in \( L^* \approx 18 \) is obtained which implies the fact that the eavesdropper is relatively prevailing. This result is intuitive, since the eavesdropper is more sophisticated compared to the one considered in Example 2. Consequently, \( L^* \approx 18 \) is suggested by both the approximation and simulation results.

\begin{align}
\text{Example 3 (Multi-antenna eavesdropper):} \quad \text{Consider a scenario with a single antenna legitimate receiver whose channel is being overheard by a sophisticated multi-antenna terminal, i.e., } N_t = 1 \text{ and } N_e \text{ growing large. Assume that the BS knows the CSI of the eavesdropper.}

\text{From Theorem 1, } \eta \text{ and } \sigma^2 \text{ are given by}

\begin{align}
\eta &= \log \left( 1 + \frac{\rho_m \ell (1 + \ln M L^{-1})}{\rho_e N_e L} \right) \quad (31a) \\
\sigma^2 &= \frac{\rho_m^2 \psi^2}{(1 + \rho_e L)^2} \left( 2 - L M^{-1} \right) + \frac{\psi^2}{L} \quad (31b)
\end{align}

\end{align}

In contrast to Example 2, \( R_{\text{Erg}}(S) \) in this example can not be approximated by \( \eta \), since \( \xi = \eta/\sigma \) is not necessarily large. Consequently, we employ (15) to accurately approximate the achievable ergodic rate. Define \( R(\cdot) \) over the real axis as

\begin{align}
R(\ell) := s(\ell) \phi \left( \frac{f(\ell)}{s(\ell)} \right) + f(x) Q \left( -\frac{f(\ell)}{s(\ell)} \right) \quad (32)
\end{align}

where \( f(\ell) \) and \( s(\ell) \) are given by

\begin{align}
f(\ell) &= \log \left( 1 + \frac{\rho_m \ell (1 + \ln M)}{(1 + \rho_e N_e) \ell} \right) \quad (33a) \\
s(\ell) &= \sqrt{\frac{\rho_m^2 \psi^2}{(1 + \rho_e L)^2} \ell (2 - \ell M^{-1}) + \frac{\psi^2}{L}} \quad (33b)
\end{align}

With similar lines of inference as in Example 2 one concludes that for any non-zero choices of \( \rho_e \) and \( \rho_m \) the eavesdropper is relatively prevailing. This result is intuitive, since the eavesdropper is more sophisticated compared to the one considered in Example 2. Consequently, \( L^* \approx |\ell^*| \) where \( |\ell^*| \) satisfies (34).
In order to investigate the prevalence, we define

\[ \mathcal{R}(\ell) := \log \left( \frac{1 + \rho L + \rho \ln(ML^{-1})}{1 + \rho \ell} \right) + \frac{\rho \psi q_0}{1 + \rho \ell} \sqrt{3 - \frac{\ell}{M}} \]  

where \( q_0 = Q^{-1}(1 - \epsilon) \). It is then trivial to show that

\[ \mathcal{R}'(\ell) := \frac{\rho \ln(M^{-1}) - \rho(1 + \rho \ell)}{\left( 1 + \rho \ell \right) (1 + \rho \ell + \rho \ln(ML^{-1}))} - \frac{q_0 \rho \psi}{2 \left( 1 + \rho \ell \right)^2 \sqrt{3M^2 - \ell M}} \]  

By standard lines of derivation, one can show that for any choices of \( \rho \), \( \mathcal{R}'(M) < 0 \). This indicates that for all SNRs the eavesdropper is relatively prevailing. Moreover, for

\[ \rho > (1 + a_\epsilon) \ln M + a_\epsilon - 1 \]  

with \( a_\epsilon := -3q_0 \psi / \sqrt{2} \), the outage secrecy rate is a decreasing function of \( L \), and therefore, \( L^* = 1 \). Nevertheless, when \( M \) does not hold, the optimal number of active transmit antennas is given by \( L^* \approx \frac{\ell^*}{M} \) where \( \ell^* \) fulfills \( \mathcal{R}'(\ell^*) = 0 \).

In Fig. 8 the \( \epsilon \)-outage secrecy rate at \( \epsilon = 0.1 \) for \( M = 128 \) has been plotted versus \( L \) for \( \log \rho = -15 \text{ dB} \) and \( \log \rho = 15 \text{ dB} \). As the figure depicts, for the latter case, in which the inequality in (38) is satisfied, \( \mathcal{R}_{\text{out}}(\epsilon) \) is a decreasing function of \( L \). For the case of \( \log \rho = -15 \text{ dB} \), the simulations indicate that \( L^* = 23 \). The analytic investigations moreover reports \( \ell^* = 22.97 \) which is consistent with the simulation results.

**VI. CONCLUSION**

In this paper, we characterized the impacts of TAS on the secrecy performance of massive MIMO wiretap setups. It was shown that in some scenarios, the secrecy performance is enhanced under TAS compared to the case of full complexity. We moreover developed an analytic framework to determine the optimal number of active antennas in these scenarios. The numerical investigations confirmed the accuracy of our framework even for settings with not so large dimensions. The analyses of this study implies that antenna selection in some massive MIMO wiretap setups enhances the secrecy performance. A possible direction for future work is to extend the current framework to scenarios in which other techniques, such as artificial noise generation, are employed along with TAS for secrecy enhancement. The work in this direction is ongoing.

1One should note that for \( L^* = 1 \), we have \( \beta_0 = 1 \), and therefore, this approximation is not necessarily consistent. Nevertheless, as shown through numerical investigations, the approximation is accurate even in this regime.
**APPENDIX A**

**DERIVATION OF THEOREM 1**

We start by evaluating the large-system distribution of $\mathcal{R}_m$. It has been shown in [28] Lemma 2 that the distribution of the input-output mutual information of a Gaussian MIMO channel, under some constraints, is accurately approximated in terms of the random variables $\text{Tr}\{J\}$ and $\text{Tr}\{J^2\}$ where $J \equiv H^H H$. Under the TAS protocol $\mathcal{S}$, $\text{Tr}\{J\}$ represents the sum of $L$ first order statistics which at the large limit of $M$ converges in distribution to a Gaussian random variable whose mean and variance are given by (10b) and (10b), respectively. Using some properties of random matrices, the large-system distribution of $\mathcal{R}_e$ is then approximated as in [28] Theorem 1 with a Gaussian distribution whose mean and variance are given in terms of $\eta_e$ and $\sigma_e^2$. The next step is to evaluate the distribution of $\mathcal{R}_e$. Noting that the main and the eavesdropper channel are independent, it is concluded that the TAS protocol $\mathcal{S}$ performs as a random selection protocol from the eavesdropper’s point of view. By considering the asymmetrical asymptotic regime of eavesdropping, one can invoke the asymptotic results for i.i.d. Gaussian fading channels in [45], and approximate the large-system distribution of $\mathcal{R}_e$ with a Gaussian distribution whose mean and variance respectively read

$$
\eta_e = U_e \log (1 + \rho_e V_e)
$$

$$
\sigma_e^2 = \left(1_{\{N_e > L\}} \frac{U_e}{V_e} + 1_{\{N_e < L\}} \frac{U_e V_e \rho_e^2}{(1 + \rho_e V_e)^2}\right) \psi^2.
$$

Since the main and the eavesdropper channel are independent, $\mathcal{R}^* = \mathcal{R}_m - \mathcal{R}_e$ is sum of two independent Gaussian random variables in the large-system limit; hence, it is Gaussian with mean and variance given in (14a) and (14b).

**APPENDIX B**

**DERIVATION OF THEOREM 2**

In the large-system limit, the achievable ergodic and $\epsilon$-outage secrecy rate are accurately approximated by (15) and (19), respectively. To derive a sufficient condition, we first consider Scenario A. We define the function $\mathcal{M}_A(\cdot)$ on the real axis as

$$
\mathcal{M}_A(\ell) = s(\ell) \phi \left( \frac{f(\ell)}{s(\ell)} \right) + f(\ell) Q \left( \frac{-f(\ell)}{s(\ell)} \right)
$$

where $f(\ell)$ and $s(\ell)$ are determined by replacing $L$ with $\ell$ in the asymptotic terms given for $\eta$ and $\sigma$ in Theorem 1 respectively. $\mathcal{M}_A(\ell)$ is the real envelope of the achievable ergodic rate whose values at integer points within the interval $[1, M]$ give $\mathcal{R}_{\mathrm{Erg}}(S)$. It is therefore concluded that for the set of $T = (\rho_m, \rho_e, N_e, N_t)$ in which $\mathcal{M}_A(\ell)$ is an increasing function, the legitimate receiver is relatively prevailing. In this case, a set of sufficient conditions are deduced by investigating the set of tuples in which $\mathcal{M}_A(\ell) > 0$ for all $\ell \in [1, M]$. To extend the result to Scenario B, one may similarly define

$$
\mathcal{M}_B(\ell) = f(\ell) - \psi^{-1}(\epsilon) s(\ell)
$$

and investigate a sufficient condition for which $\mathcal{M}_B(\ell) > 0$.

**Lemma 1:** Assume that $f'(\ell) > 0$ for $\ell \in [1, M]$. Then,

(a) $s'(\ell) \approx 0$ for $\ell < \min \{N_e, N_t\}$, and

(b) $f(\ell)/s(\ell) \approx 1$ for $\ell \in [1, M]$.

**Proof:** Let $f'(\ell) > 0$. In this case, for $\ell < \min \{N_e, N_t\}$, one can simply show that

$$
N_e \rho_e < \frac{N_f \rho_m u}{N_t + \rho_m \eta_e} (1 + \rho_e \ell)
$$

where $u$ and $\eta_e$ are defined in Theorem 2. As we have assumed an asymmetrically asymptotic regime of eavesdropping, the number of eavesdropper antennas read $N_e \gg \ell$ when $\ell < \min \{N_e, N_t\}$. This means that the inequality in (42) holds only when $u$ takes values close to zero. By taking the first derivative of $s(\ell)$, it is then shown that for values of $u$ close to zero, $s'(\ell) \approx 0$ for $\ell < \min \{N_e, N_t\}$ which concludes (a).

To prove (b), one may note that for $\ell > \min \{N_e, N_t\}$ we have $s'(\ell) < 0$. This statement along with (a) depicts that

$$
\frac{\partial}{\partial \ell} \left( \frac{f(\ell)}{s(\ell)} \right) > 0
$$

when $f'(\ell) > 0$. As $f(1)/s(1) \approx 1$ for large $M$, one concludes that $f(\ell)/s(\ell) \approx 1$ for $\ell \in [1, M]$.

From Lemma 1, it is observed that $f'(\ell) > 0$ is a sufficient condition in the asymptotic regime to have both $\mathcal{M}_A(\ell) > 0$ and $\mathcal{M}_B(\ell) > 0$. In fact, by using Part (b) in Lemma 1 we employ $Q(-\xi) \approx 1 - \phi(\xi)/\xi$ and write $\mathcal{M}_A(\ell) = f'(\ell)$ when $f'(\ell) > 0$. This concludes the proof for Scenario A. Moreover,

$$
\mathcal{M}_B(\ell) = h'(\ell) - \psi^{-1}(\epsilon) s'(\ell).
$$

Note that $s'(\ell) < 0$ for $\ell \in [\min \{N_e, N_t\}, M]$. Hence, along with Part (a) in Lemma 1 implies that $f'(\ell) > 0$ is a sufficient condition for Scenario B as well. Finally, by taking the derivative of $f'(\ell)$ and noting that $\partial \eta_e/\partial \ell = u$, the proof is completed.

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1Definition indicates that in this regime $\beta_e = N_e/L$ reads either $\beta_e < 1$ or $\beta_e \gg 1$. 
