A New Transmit Antenna Selection Technique for Physical Layer Security with Strong Eavesdropping

Gonzalo J. Anaya-López  
Instituto de Telecomunicación (TELMA)  
Universidad de Málaga  
Málaga 29010, Spain  
gjal@ic.uma.es

J. Carlos Ruiz-Sicilia  
Dept. of Communication Engineering  
Universidad de Málaga  
Málaga 29071, Spain  
jcrs@ic.uma.es

F. Javier López-Martínez  
Instituto de Telecomunicación (TELMA)  
Universidad de Málaga  
Málaga 29010, Spain  
fjlopezm@ic.uma.es

Abstract—We propose a new transmit antenna selection (TAS) technique that can be beneficial for physical layer security purposes. Specifically, we show that the conventional TAS criterion based on the legitimate channel state information (CSI) is not recommended when the average signal-to-noise ratio for the illegitimate user becomes comparable or superior to that of the legitimate user. We illustrate that an eavesdropper’s based antenna selection technique outperforms conventional TAS, without explicit knowledge of the eavesdropper’s instantaneous CSI. Analytical expressions and simulation results to support this comparison are given, showing how this new TAS scheme is a better choice in scenarios with a strong eavesdropper.

Index Terms—Secrecy capacity, physical layer security, wireless security, attacks, fading channels

I. INTRODUCTION

Security in wireless communications is a critical issue due to the inherent broadcast nature of the wireless channel. Cryptographic techniques based on complex mathematical functions must be updated as computing power advances [1]. In addition, the advent of the Internet of Things (IoT) with energy and power limited devices demands strategies that do not incur in a high computational burden or complex key distribution protocols with high network overheads. For this reason, the information theoretic approaches based on physical layer security (PLS) have become an alternative to provide security in wireless environments [2, 3].

PLS techniques make use of the physical characteristics of the wireless channel in order to achieve the desired security. Wyner in [4] proved the existence of codes for the wiretap channel that guarantee security with this complementary technique to the traditional approach. Later, in [5] this work was extended to the Gaussian wiretap and the secrecy capacity was defined as the difference between the main channel capacity and the eavesdropper’s one, being the former capacity always greater than the latter.

Motivated by the advances of multiple antennas systems in wireless communication, complex beamforming techniques were considered [6, 7] to improve channel security. However, this solution requires a higher complexity and additional computational cost that increases with the number of antennas [8, 9]. Hence, we propose the alternative transmit antenna selection (TAS) [8], which requires only one radio-frequency (RF) chain and therefore reduces the hardware complexity [10, 11].

TAS techniques are useful to reduce the hardware complexity of transmitters while retaining some of the benefits conveyed by multi-antenna transmission [8]. For this reason, they have also been exploited in the context of PLS. Classically, TAS strategies for PLS rely on a sub-optimal selection criterion that is solely based on the channel state information (CSI) of the legitimate link [11, 12]. The optimal TAS criterion that maximizes the achievable secrecy rates requires perfect CSI knowledge for both the legitimate and eavesdropper’s links [13], which may not be always possible in practice, and incurs in an additional complexity penalty.

In this work, we investigate whether conventional TAS techniques are always the best choice from a PLS perspective. Specifically, we evaluate the performance of an eavesdropper’s based TAS scheme. This technique can be implemented with low feedback and low signal processing cost since, as in the legitimate’s based TAS scheme [12], only the index of the worst antenna for the Eve’s channel is required. We show that this new criterion outperforms conventional TAS techniques as those in [11-14] in the strong eavesdropper regime [16], i.e., when the average signal-to-noise ratio (SNR) for the eavesdropper is comparable or larger than the legitimate SNR.

Figure 1. System model under consideration. The DL transmission of the message $z_B$ by the BS (Alice) takes place through the transmit antenna $k$, which is selected according to some TAS criterion.
II. System Model

We consider a mobile communications scenario as in Fig. 1, where the base station (BS) is equipped with $M$ antennas while the receivers are single-antenna users. The BS is equipped with a single RF chain, and hence uses TAS to exploit the spatial diversity due to the use of a multi-antenna configuration. We also take the conventional assumption that all wireless channels are affected by independent quasi-static fading, which are constant during the transmission of an entire codeword. In order to communicate with the set of served users $\mathcal{V}$ within its coverage area, a time-division duplexing (TDD) protocol is considered. Due to channel reciprocity, CSI from each user can be acquired from the uplink (UL) transmissions.

For the downlink (DL) transmission, the BS can operate in two modes, which we denote as secure and standard modes. In the former, the BS aims to communicate securely with a certain user $v_i = B$, for which the placeholder name Bob is conventionally used. At the same time, a different user (eavesdropper, or Eve) $v_j = E$ aims to intercept and decode the communication, taking advantage of the broadcast nature of the wireless transmission. In the latter mode, the BS transmits a set of messages $z_v$ with $\mathbb{E}\{|z_v|^2\} = 1$ to each and every user $v \in \mathcal{V}$. Regardless of the DL transmission mode, the BS uses a TAS scheme with a certain antenna selection criterion.

Now, focusing on the DL transmission in secure mode, the BS transmits the message $z_B$ with $\mathbb{E}\{|z_B|^2\} = 1$ through the $k$-th selected antenna according to the TAS scheme. Therefore, the signal received at Bob from the BS in the DL transmission is given by

$$y_B^{\text{TAS}} = P_T R_B^{-\alpha} h_B^{\text{TAS}} z_B + n_B,$$  

whereas the signal received at the eavesdropper is given by

$$y_E^{\text{TAS}} = P_T R_E^{-\alpha} h_E^{\text{TAS}} z_B + n_E,$$  

where $P_T$ denotes the transmit power, $n_B$ and $n_E$ are the additive white Gaussian noise (AWGN) components at each receiver, with $\mathbb{E}\{|n_B|^2\} = N_0$, $R_B$ and $R_E$ are the distances between the BS and Bob/Eve, respectively, and $\alpha$ is the path-loss exponent. The channel coefficients $h_u^{\text{TAS}} = h_u^{(k)}$, with $u = \{B, E\}$, correspond to those between the $k$-th transmit antenna and each receiver, so that $h_u^{\text{TAS}} \in [h_u^{(1)}, \ldots, h_u^{(M)}]$ and the channel coefficients $h_u^{(i)}$ are normalized as $\mathbb{E}\{|h_u^{(i)}|^2\} = 1$. From (1) and (2) we can define the instantaneous SNRs at the legitimate and eavesdropper’s sides as

$$\gamma_B = \frac{P_T R_B^{-\alpha}}{N_0} |h_B^{\text{TAS}}|^2 |z_B|^2$$  

and

$$\gamma_E = \frac{P_T R_E^{-\alpha}}{N_0} |h_E^{\text{TAS}}|^2 |z_B|^2.$$  

As aforementioned, we first assume that perfect CSI is available for every user in the system, which is acquired during the UL transmission; this condition will be later relaxed. Hence, the maximum reliable and secure transmission rate is defined by the average secrecy capacity (ASC):

$$\overline{C}_S = \mathbb{E}\{ C_S(\gamma_B, \gamma_E) \},$$  

where $C_S(\gamma_B, \gamma_E)$ is the instantaneous secrecy capacity defined as

$$C_S(\gamma_B, \gamma_E) \triangleq \log_2 (1 + \gamma_B) - \log_2 (1 + \gamma_E),$$

where $[\cdot]^+$ is used to denote that $C_S = 0$ when the argument within brackets is negative. When a random antenna is selected for transmission, the coefficients $h_B^{\text{TAS}}$ and $h_E^{\text{TAS}}$ have the same distribution as if a single-antenna BS was considered, i.e., there is no gain having multiple-antennas at the BS. However, this situation changes when a TAS criterion other than random is considered. In the following subsections, we discuss how the use of different TAS schemes affects the achievable secrecy rates defined in (6).

A. Optimal TAS

The optimal transmit antenna selection (O-TAS) scheme selects the transmit antenna that provides the best instantaneous transmission rate for the system [15], i.e., maximizes the instantaneous secrecy capacity in (6). To this end, it is required perfect CSI of the legitimate and the eavesdropper channel. The average SNRs for these channels is given as follows:

$$\overline{\gamma}_B = \frac{P_T R_B^{-\alpha}}{N_0} \mathbb{E}\{|h_B^{\text{TAS}}|^2\} = \overline{\gamma}_{B_0} \mathbb{E}\{|h_B^{\text{TAS}}|^2\}$$

and

$$\overline{\gamma}_E = \frac{P_T R_E^{-\alpha}}{N_0} \mathbb{E}\{|h_E^{\text{TAS}}|^2\} = \overline{\gamma}_{E_0} \mathbb{E}\{|h_E^{\text{TAS}}|^2\},$$

where $\overline{\gamma}_{B_0}$ and $\overline{\gamma}_{E_0}$ are the average SNRs in the case of a single-antenna transmitter. With these definitions, we can obtain the $k$-th antenna that maximizes the rate of secure transmission using the following selection criterion:

$$k = \arg \max_{1 \leq i \leq M} \left\{ \log_2 \left( \frac{1 + \overline{\gamma}_{B_0} |h_B^{(i)}|^2}{1 + \overline{\gamma}_{E_0} |h_E^{(i)}|^2} \right) > 0 \right\}.$$  

Hence, the selection criterion aims at maximizing the random variable $X_i$, built as a generalized ratio of Bob’s and Eve’s instantaneous SNRs. This is only possible when perfect CSI for all channels is available at the BS, yielding:

$$\overline{C}_{S \text{-TAS}} = \mathbb{E}\left\{ \log_2 \left( \frac{1 + \overline{\gamma}_{B_0} |h_B^{(i)}|^2}{1 + \overline{\gamma}_{E_0} |h_E^{(i)}|^2} \right) > 0 \right\}.$$  

B. Bob-based TAS

The Bob-based transmit antenna selection (B-TAS) scheme is the state-of-the-art technique usually associated with TAS [11,14] in the PLS literature. Under this criterion, the antenna that maximizes the legitimate channel transmission rate is selected, instead of maximizing the secrecy capacity. For this reason, it is regarded as a sub-optimal scheme [17]. Despite not
selecting the best possible antenna from a secrecy perspective, this scheme is popular in practice compared to O-TAS because it does not require eavesdropper’s CSI. Besides, full Bob’s CSI is also not required to implement this TAS scheme, since the antenna index information can be retrieved from Bob using a low-rate feedback channel, or estimated at Alice using an energy detector. With this scheme, the antenna selection criterion is simpler, as it is just a function of the legitimate channel coefficients:

\[
h_{B}^{TAS} = \max_{i=1,\ldots,M} \left\{ \frac{|h_B^{(i)}|^2}{\beta_i} \right\},
\]

where the distribution of \(h_{B}^{TAS}\) is defined by the maximum (or \(M\)-th order) statistic \[18\] as follows when \(h_B^{(i)} \forall i = 1,\ldots,M\) are independent and identically distributed:

\[
F_B^M(x) = \frac{1}{\text{ln} 2} \int_0^\infty \frac{F_E(x) [1 - F_B(x)]}{1 + x} \, dx,
\]

where \(F_E(x)\) is the cumulative distribution function (CDF) of a single fading coefficient. Note that the distribution in \[12\] depends on the number of antennas \(M\) among which the selection is made. Conversely, the distribution of \(h_{E}^{TAS}\) is not altered by the B-TAS selection criterion.

C. E-TAS

The last scheme to analyze, which is originally presented in this work to the best of the authors’ knowledge, is referred to as Eve-based transmit antenna selection (E-TAS). This scheme aims to improve the system’s secrecy performance by selecting the transmit antenna solely based on the eavesdropper’s channel. The rationale behind this scheme comes from the observation that B-TAS criterion tends to behave as the O-TAS criterion as the eavesdropper’s SNR is reduced, i.e. \(\gamma_{E_0} |h_E^{(i)}|^2 \ll 1\) in \[10\], since the latter becomes immaterial in the maximization process. Based on this observation, we conjecture that an E-TAS criterion aimed at minimizing the rate of Eve’s channel should perform reasonably close to O-TAS when the eavesdropper’s channel has a better average SNR than the legitimate channel; this is the case, for instance, of scenarios with near users \[19\] or strong eavesdroppers \[16\]. In other words, it is the denominator in \[10\] that would dominate in the antenna selection.

Secrecy capacity can be improved by either increasing the capacity of the legitimate channel or decreasing the capacity of the eavesdropper channel. Therefore, the E-TAS scheme improves secrecy capacity by selecting the antenna that presents the worst channel for the eavesdropper. In this way, the legitimate’s CSI is not required in the selection criterion:

\[
h_{E}^{TAS} = \min_{i=1,\ldots,M} \left\{ \frac{|h_E^{(i)}|^2}{\beta_i} \right\},
\]

while the distribution of \(h_{B}^{E-TAS}\) is not changed by the E-TAS selection criterion. Note that in our scheme the eavesdropper’s CSI is available at the BS from the UL transmission phase; however, this is not explicitly required to implement the antenna selection criterion. Instead, a simple antenna-wise energy detection technique at the BS during the UL transmission is enough to implement the E-TAS criterion. Although targeting the eavesdropper is unusual, our aim is to demonstrate how in scenarios where perfect CSI is not available, choosing the B-TAS criterion can be far from an optimal decision.

III. PHYSICAL LAYER SECURITY

We now evaluate the average secrecy capacity for the E-TAS scheme, as the figure of merit to compare the secrecy performances. Evidently, in all instances the performance upper-bound will be provided by the O-TAS scheme, since the antenna selection criterion incorporates both Bob’s and Eve’s CSI. In the following, for the sake of simplicity and ease of discussion, we assume the case of Rayleigh fading.

For the O-TAS scheme, we gently refer to the results obtained in \[15\], eq. (13), which have a rather complicated form due to the intricate nature of the distribution of the equivalent random variable (RV) \(X\) in \[9\].

In order to obtain the expression of the sub-optimal schemes in a simpler way, we use the ASC formulation in \[20\], eq. (12):

\[
\mathcal{C}_S (\tau_B, \tau_E) = \frac{1}{\ln 2} \int_0^\infty F_E(x) \left[1 - F_B(x)\right] \, dx,
\]

where \(F_B(\cdot)\) and \(F_E(\cdot)\) represent the CDFs of \(\gamma_B\) and \(\gamma_E\), respectively.

Since we assumed complex Gaussian distributed channel coefficients, we have that the channel coefficients not affected by the selection criteria, i.e., \(h_{E}^{B-TAS}\) and \(h_{B}^{B-TAS}\), are exponentially distributed with CDF:

\[
F_{\exp}(x, \beta) = 1 - \exp \left(\frac{-x}{\beta}\right),
\]

where \(\beta\) is the mean of an exponential distribution.

Substituting \[12\] and \[16\] in \[15\], applying the binomial theorem and after some manipulations, we obtain the ASC for the B-TAS scheme:

\[
\mathcal{C}_S^{B-TAS} = \frac{1}{\ln 2} \int_0^\infty F_{\exp}(x, \tau_{E_0}) \left[1 - F_{\exp}(x, \tau_{B_0})\right] \, dx
\]

\[
= \frac{1}{\ln 2} \sum_{k=1}^M \binom{M}{k} (-1)^{k+1} \Delta \mathcal{E} \left(\frac{k}{\tau_{B_0}}, \frac{1}{\tau_{E_0}} + \frac{k}{\tau_{B_0}}\right),
\]

where \(\Delta \mathcal{E}(\cdot)\) is an auxiliary function defined as

\[
\Delta \mathcal{E}(A, B) = e^A E_1(A) - e^B E_1(B),
\]

where \(E_1(\cdot)\) is the exponential integral function \[21\] eq. (5.1.1).
Finally, we obtain the ASC for the E-TAS scheme by substituting (14) and (16) in (15), as:

$$C_{S}^{E-TAS} = \frac{1}{\ln 2} \int_{0}^{\infty} F_{E}^{1}(x) \left[1 - F_{\exp}(x, \gamma_{B0})\right]dx$$

$$= \frac{1}{\ln 2} \Delta \varepsilon \left(\frac{1}{\gamma_{B0}}, \frac{M}{\gamma_{E0}} + \frac{1}{\gamma_{B0}}\right).$$

$$\tag{19}$$

Interestingly, expression (19) has the exact same functional form as that originally deduced in Bloch’s paper [3, eq. 5] for the single-antenna case and Rayleigh fading. However, in the case of (19) we see that the eavesdropper’s average SNR is reduced by a factor of $M$. This implies that the effective SNR of the eavesdropper is reduced as the number of antennas is increased, which is beneficial for physical layer security.

### IV. Numerical Results

In this section we study the performance of the proposed schemes for physical layer security purposes. Monte Carlo (MC) simulations are included in all instances to double-check the validity of the analytical results.

In Fig. 2 the ASC is evaluated for all the three schemes, as a function of the reference average SNR at the legitimate receiver $\gamma_{B0}$ and a fixed value of $\gamma_{E0} = 10$ dB. The cases with $M = 2$ and $M = 8$ antennas are included with dash-dotted and solid lines, respectively. We see that the best possible performance is evidently obtained by the O-TAS scheme, and that the performance gap with the sub-optimal schemes grows as $M$ is increased. One important observation is that the classical B-TAS scheme only outperforms the newly proposed E-TAS scheme for a sufficiently large $\gamma_{B0}$. The performance gap between both sub-optimal schemes in the asymptotic regime is barely modified by increasing the number of antennas, and there is a range of SNR values for which E-TAS performs better than B-TAS, as both the legitimate and eavesdropper’s SNRs become comparable.

In order to better investigate this behavior, we now evaluate in Fig. 3 the ASC as a function of $\gamma_{E0}$, for a fixed value of $\gamma_{B0} = 10$ dB. Again, the cases with $M = 2$ and $M = 8$ are considered. We can see how the O-TAS scheme acts as the upper-bound of the sub-optimal schemes. We observe that as the eavesdropper’s SNR grows, the E-TAS scheme not only outperforms conventional B-TAS, but also starts behaving closely to the O-TAS scheme. At the extremes, where the SNR value of one of the channels predominates, the sub-optimal scheme that better approximates O-TAS is that whose predominant parameter is used in the selection criterion, see (11) and (13). Indeed, the ASC is decreased in all instances as the eavesdropper’s SNR grows, and is increased when more antennas are used.

In order to evaluate the relative performance loss compared to the optimal TAS scheme, and its interplay with the relation between the legitimate and eavesdropper’s SNRs, we represent in Fig. 4 the ASCs normalized to that of the O-TAS case as a function of the ratio $\gamma_{E0}/\gamma_{B0}$. The case with $M = 8$ antennas is used for exemplary purposes, and three different values for $\gamma_{B0}$ are also used. As mentioned above, the best sub-optimal scheme varies considerably depending on the dominant channel, black dots are included to highlight when the best scheme changes from B-TAS to E-TAS. From the figure we can extract several insights: (i) E-TAS performs closer to the optimal scheme for a wider range of SNR values; (ii) E-TAS is the best sub-optimal choice for the strong eavesdropper regime [16, 19] (gray shaded area in the figure); (iii) an adaptive transmission scheme able to switch between
E-TAS and B-TAS criteria depending on the average SNRs and antenna-index information is recommended to enhance secrecy performance.

V. CONCLUSION

We presented a new TAS technique for PLS, which is well-suited for scenarios on which antenna-quality information from the eavesdropper can be attained. By implementing a TAS criterion which seeks to minimize the receive SNR at the eavesdropper’s side, we obtain noticeable performance gains for a wide range of SNRs compared to the conventional TAS criterion classically used for PLS when perfect CSI is not available. Results also show that the performance of the proposed E-TAS scheme without explicit CSI knowledge is close to the optimal scheme with full CSI in the strong eavesdropper’s regime. The implementation of the E-TAS technique may be well-suited for scenarios with strong eavesdroppers, and requires to have some sort of antenna quality indicator for the eavesdropper’s channel. This can be done by exploiting the eavesdropper’s RF leakages and using energy detection techniques.

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Figure 4. Normalized average secrecy capacity (C_S/C_O)−TAS as a function of \( \frac{\gamma_{E0}}{\gamma_{B0}} \), for different values of \( \gamma_{E0} = \{ 10, 20, 30 \} \) dB. These correspond to the solid, dashed and dash-dotted lines in the figure, respectively, with \( M = 8 \). Markers correspond to MC simulations. The crossing SNR value is identified with a solid black marker for each pair of curves.