A Note on the Secrecy Capacity of the Multi-antenna Wiretap Channel

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Abstract

Recently, the secrecy capacity of the multi-antenna wiretap channel was characterized by Khisti and Wornell [1] using a Sato-like argument. This note presents an alternative characterization using a channel enhancement argument. This characterization relies on an extremal entropy inequality recently proved in the context of multi-antenna broadcast channels, and is directly built on the physical intuition regarding to the optimal transmission strategy in this communication scenario.

1 Introduction

Consider a multi-antenna wiretap channel with \( n_t \) transmit antennas and \( n_r \) and \( n_e \) receive antennas at the legitimate receiver and the eavesdropper, respectively:

\[
\begin{align*}
y_r[m] &= H_r x[m] + w_r[m] \\
y_e[m] &= H_e x[m] + w_e[m]
\end{align*}
\]

where \( H_r \in \mathbb{R}^{n_r \times n_t} \) and \( H_e \in \mathbb{R}^{n_e \times n_t} \) are the channel matrices associated with the legitimate receiver and the eavesdropper. The channel matrices \( H_r \) and \( H_e \) are assumed to be fixed during the entire transmission and are known to all three terminals. The additive noise \( w_r[m] \) and \( w_e[m] \) are white Gaussian vectors with zero mean and are independent across the time index \( m \). The channel input satisfies a total power constraint

\[
\frac{1}{n} \sum_{m=1}^{n} \| x[m] \|^2 \leq P.
\]
The secrecy capacity is defined as the maximum rate of communication such that the information can be decoded arbitrarily reliably at the legitimate receiver but not at the eavesdropper.

For a discrete memoryless wiretap channel $P(Y_r, Y_e|X)$, a single-letter expression for the secrecy capacity was obtained by Csiszár and Körner [2] and can be written as

$$C = \max_{P(U,X)} [I(U;Y_r) - I(U;Y_e)]$$

where $U$ is an auxiliary random variable over a certain alphabet that satisfies the Markov relation $U - X - (Y_r, Y_e)$. Moreover, (3) extends to continuous alphabet cases with power constraint, so the problem of characterizing the secrecy capacity of the multi-antenna wiretap channel reduces to evaluating (3) for the specific channel model (1).

Note that evaluating (3) involves solving a functional, nonconvex optimization problem. Solving optimization problems of this type usually requires nontrivial techniques and strong inequalities. Indeed, for the single-antenna case ($n_t = n_r = n_e = 1$), the capacity expression (3) was successfully evaluated by Leung and Hellman [3] using a result of Wyner [4] on the degraded wiretap channel and the celebrated entropy-power inequality [5, Cha. 16.7]. (Alternatively, it can also be evaluated using a classical result from estimation theory via a relationship between mutual information and minimum mean-squared error estimation [6].) Unfortunately, the same approach does not extend to the multi-antenna case, as the latter, in its general form, belongs to the class of nondegraded wiretap channels. The problem of characterizing the secrecy capacity of the multi-antenna wiretap channel remained open until the recent work of Khisti and Wornell [1].

In [1], Khisti and Wornell followed an indirect approach to evaluate the capacity expression (3) for the multi-antenna wiretap channel. Key to their evaluation is the following genie-aided upper bound

$$I(U;Y_r) - I(U;Y_e) \leq I(U;Y_r, Y_e) - I(U;Y_e)$$

$$= I(X;Y_r, Y_e) - I(X;Y_e)$$

$$\leq I(X;Y_r, Y_e) - I(X;Y_e)$$

$$= I(X;Y_r|Y_e)$$

where (5) follows from the Markov chain $U - X - (Y_r, Y_e)$, and (6) follows from the trivial inequality $I(X;Y_r, Y_e|U) \geq I(X;Y_e|U)$. Khisti and Wornell [1] further noticed that the original objective of optimization $I(U;Y_r) - I(U;Y_e)$ depends on the channel transition probability $P(Y_r, Y_e|X)$ only through the marginals $P(Y_r|X)$ and $P(Y_e|X)$, whereas the upper bound $I(X;Y_r|Y_e)$ does depend on the joint conditional $P(Y_r, Y_e|X)$. A good upper bound on the secrecy capacity is thus contrived as

$$C = \max_{P(U,X)} [I(U;Y_r) - I(U;Y_e)] \leq \min_{P(Y'_r, Y'_e|X) \in \mathcal{D}} \max_{P(X)} I(X;Y'_r|Y'_e) = \max_{P(X)} \min_{P(Y'_r, Y'_e|X) \in \mathcal{D}} I(X;Y'_r|Y'_e)$$
where $\mathcal{D}$ is a set of joint conditionals $P(Y'_r,Y'_e|X)$ satisfying

$$P(Y'_r|X) = P(Y_r|X) \quad \text{and} \quad P(Y'_e|X) = P(Y_e|X). \quad (9)$$

The upper bound $\min_{P(Y'_r,Y'_e|X)\in\mathcal{D}} \max_{P(X)} I(X;Y'_r|Y'_e)$ has a specific physical meaning: it is the secrecy capacity of the wiretap channel $P(Y'_r,Y'_e|X)$ where the legitimate user has access to both $Y_r$ and $Y_e$, minimized over the worst cooperation between the legitimate receiver and the eavesdropper. In essence, this is very similar to the Sato upper bound on the sum capacity of a general broadcast channel [7]. For the multi-antenna wiretap channel, Khisti and Wornell [1] showed that the conditional mutual information $I(X;Y'_r|Y'_e)$ is maximized when the channel input $X$ is Gaussian. Hence, the upper bounds in (8) can be written as a saddle-point matrix optimization problem. By comparing the value of the optimal Gaussian solution for the original optimization problem $\max_{P(U,X)} [I(U;Y_r) - I(U;Y_e)]$ with the upper bounds in (8), Khisti and Wornell [1] showed that the results are identical and thus established the optimality of both matrix characterizations for the multi-antenna wiretap channel. Operationally, Khisti and Wornell [1] showed that the original multi-antenna wiretap channel has the same secrecy capacity as when the legitimate user has access to both received signals and optimized over the worst cooperation between the legitimate user and the eavesdropper. (The same approach was also followed by Shafiee et al. [8] and Oggier and Hassibi [9] to characterize the secrecy capacity of the $2 \times 2 \times 1$ and the general multi-antenna wiretap channel, respectively.) Considering the disparity between these two physical scenarios, this is a rather surprising result.

The approach of Khisti and Wornell [1] also reminds us of the degraded same marginals bound for the capacity region of the multi-antenna broadcast channel [10][11]. There, the optimality of the Gaussian input is hard to come by, and a precise characterization of the capacity region had to wait until the proposal of a drastically different approach by Weingarten et al. [12]. Motivated by the line of work on the multi-antenna broadcast channel, in this note we present a different approach to characterize the secrecy capacity of the multi-antenna wiretap channel. Our approach is based on an extremal entropy inequality recently proved in the context of multi-antenna broadcast channels [13][14], and is directly built on the physical intuition regarding to the optimal transmission strategy in this communication scenario.
2 Capacity Characterization via a Channel Enhancement Argument

2.1 Capacity characterization

We consider a canonical version of the channel (vector Gaussian wiretap channel)

\[ y_r[m] = x[m] + w_r[m] \]
\[ y_e[m] = x[m] + w_e[m], \]

(10)

where \( x[m] \) is a real input vector of length \( t \), and \( w_r[m] \) and \( w_e[m] \) are additive Gaussian noise vectors with zero mean and covariance matrices \( K_r \) and \( K_e \) respectively and are independent across the time index \( m \). The noise covariance matrices \( K_r \) and \( K_e \) are assumed to be positive definite. The channel input satisfies a power-covariance constraint

\[ \frac{1}{n} \sum_{m=1}^{n} x[m] x^t[m] \preceq S \]

(11)

where \( S \) is a positive definite matrix of size \( t \times t \), and “\( \preceq \)" represents “less or equal to” in the positive semidefinite partial ordering between real symmetric matrices. Note that (11) is a rather general constraint that subsumes many other constraints including the total power constraint (2). Following [12, Sec. 5], it can be shown that for any channel gain matrices \( H_r \) and \( H_e \), there exists a sequence of vector Gaussian wiretap channels (10) whose capacities approach that of the multi-antenna wiretap channel (1). Without loss of generality, we shall focus on the vector Gaussian wiretap channel (10) with power-covariance constraint (11) for the rest of the note.

We first present a matrix characterization for the secrecy capacity of a degraded vector Gaussian wiretap channel.

**Theorem 1:** If there exists a positive semidefinite matrix \( K^*_x \preceq S \) such that

\[ (K^*_r + K_r)^{-1} = (K^*_x + K_e)^{-1} + M_2 \]
\[ (S - K^*_x)M_2 = 0 \]

(12)

for some positive semidefinite matrix \( M_2 \), the secrecy capacity of a degraded vector Gaussian wiretap channel (10) with \( K_r \preceq K_e \) can be written as

\[ C = \frac{1}{2} \log \det (I + K^*_x K_r^{-1}) - \frac{1}{2} \log \det (I + K^*_x K_e^{-1}) \]

(13)

Theorem 1 states that if there exists a positive semidefinite matrix \( K^*_x \preceq S \) that satisfies (12), then \( U = X \sim \mathcal{N}(0, K^*_x) \) is an optimal choice for the capacity expression (3) of a degraded vector
Gaussian wiretap channel. Note that this provided a sufficient condition to evaluate optimality for a specific choice of \((U, X)\). To put in perspective, proving the optimality of Gaussian \(U = X\) for the degraded vector Gaussian wiretap channel can be done with relative ease using, for example, the worst additive noise result of Diggavi and Cover [15]. However, even within the Gaussians, it is not clear how one could obtain a sufficient condition for the optimal choice of the covariance matrix, as the matrix optimization problem is (once again) a nonconvex one and the standard Karush-Kuhn-Tucker (KKT) condition is (a priori) only a necessary condition.

Proof of Theorem 1: For a degraded wiretap channel \(P(Y_r, Y_e|X)\), Wyner [4] showed that the secrecy capacity is given by
\[
\max_{P(X)} [I(X;Y_r) - I(X;Y_e)].
\] (14)
It thus follows that the secrecy capacity of a degraded vector Gaussian wiretap channel \(10\) with \(K_r \preceq K_e\) can be written as
\[
C = \max_{f(X): E[XX^t] \preceq S} [h(X + W_r) - h(X + W_e)] - \left( \frac{1}{2} \log \det K_r - \frac{1}{2} \log \det K_e \right).
\] (15)
where \(W_r\) and \(W_e\) are length-\(t\) Gaussian vectors with zero mean and covariance matrix \(K_r\) and \(K_e\) respectively and are independent of \(X\). As a special case of Lemma 2 in [14], we have
\[
\max_{f(X): E[XX^t] \preceq S} [h(X + W_r) - h(X + W_e)] \leq \frac{1}{2} \log \det \left( K_x^* + K_r \right) - \frac{1}{2} \log \det \left( K_x^* + K_e \right).\] (16)
(Inequality (17) was also implicitly used in [13, Appendix C]. For completeness, a proof is included in Appendix A.) Substituting (17) into (16), we obtained the desired result (13). This completes the proof. 

Next, we use a channel enhancement argument to lift the result of Theorem 1 to the general vector Gaussian wiretap channel. Channel enhancement argument was first introduced by Weingarten et al. [12] to characterize the capacity region of the multi-antenna broadcast channel. Here, adaptations are made to fit our purposes. The difference between the channel enhancement argument here and that of Weingarten et al. [12] will be explained at the end of Sec. 2.2.

**Theorem 2**: The secrecy capacity of a general vector Gaussian wiretap channel \(10\) can be written as
\[
C = \max_{0 \preceq K_x \preceq S} \left[ \frac{1}{2} \log \det \left( I + K_x K_r^{-1} \right) - \frac{1}{2} \log \det \left( I + K_x K_e^{-1} \right) \right]
\] (18)
where an optimal \(K_x\) (denoted here as \(K^*_x\)) must satisfy
\[
(K^*_x + K_r)^{-1} + M_1 = (K^*_x + K_e)^{-1} + M_2
\]
\[
K^*_x M_1 = 0
\]
\[
(S - K^*_x)M_2 = 0
\] (19)
for some positive semidefinite matrices $M_1$ and $M_2$.

Note that unlike Theorem 1, the characterization (19) for the optimal covariance matrix $K$ is based on the standard KKT condition and hence is only a necessary condition.

Proof of Theorem 2: Let $K^*_x$ be an optimal solution to the optimization problem in (18). By the KKT condition, $K^*_x$ must satisfy the equations in (19). Recall the single-letter capacity expression (3) and let $U = X \sim \mathcal{N}(0, K^*_x)$. The secrecy capacity of a general vector Gaussian wiretap channel (10) can be bounded from below as

$$C \geq \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K^*_r^{-1} \right) - \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K^*_e^{-1} \right).$$

(20)

To prove the reverse inequality, consider a new vector Gaussian wiretap channel with legitimate receiver and eavesdropper noise covariance matrix being $\tilde{K}_r$ and $K_e$ respectively, where $\tilde{K}_r$ is defined through the equation

$$(K^*_x + \tilde{K}_r)^{-1} = (K^*_x + K_r)^{-1} + M_1.$$  

(21)

Following Lemmas 10 and 11 of [12], $\tilde{K}_r$ has the following important properties:

1. $0 \preceq \tilde{K}_r \preceq \{K_r, K_e\};$
2. $\det(\mathbf{I} + K^*_x \tilde{K}_r^{-1}) = \det(\mathbf{I} + K^*_x K^{-1}_r).$

By virtue of $\tilde{K}_r \preceq K_e$, the new vector Gaussian wiretap channel is a degraded one. Furthermore, by the first and third equation in (19) and (21) we have

$$(K^*_x + \tilde{K}_r)^{-1} = (K^*_x + K_r)^{-1} + M_2$$

$$(S - K^*_x)M_2 = 0.$$  

(22)

It thus follows from Theorem 1 that the secrecy capacity of this new channel is equal to

$$\tilde{C} = \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x \tilde{K}_r^{-1} \right) - \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K^*_e^{-1} \right)$$

(23)

$$= \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K_r^{-1} \right) - \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K^*_e^{-1} \right)$$

(24)

where the last equality is due to the second property of $\tilde{K}_r$. Note from the first property of $\tilde{K}_r$ that $\tilde{K}_r \preceq K_r$. Reducing the noise covariance matrix for the legitimate receiver can only increase the secrecy capacity, so we have

$$C \leq \tilde{C} = \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x \tilde{K}_r^{-1} \right) - \frac{1}{2} \log \det \left( \mathbf{I} + K^*_x K^*_e^{-1} \right)$$

(25)

which is the desired reverse inequality. Putting together (20) and (25) completes the proof of the theorem.

}$\blacksquare$
2.2 Physical intuition

Our approach of characterizing the secrecy capacity of the vector Gaussian wiretap channel hinges on the existence of an enhanced channel, which needs to satisfy:

1. it is degraded, so the secrecy capacity can be readily characterized;
2. it has the same secrecy capacity as the original wiretap channel.

A priori, it is not clear whether such an enhanced channel would always exist, letting alone to actually construct one.

Our intuition regarding to the existence of the enhanced channel was mainly from the parallel Gaussian wiretap channel, which is a special case of the vector Gaussian wiretap channel (10) with diagonal noise covariance matrices $K_r$ and $K_e$. In this case, it is shown in [16] that the optimal transmission strategy is to transmit only to the subchannels for which the received signal by the legitimate receiver is stronger than that by the eavesdropper. Therefore, an enhanced channel can be constructed by reducing the noise variance for the legitimate receiver in each of those subchannels to the noise variance level of the eavesdropper. Clearly, the enhanced channel thus constructed is a degraded parallel Gaussian broadcast channel. Furthermore, the secrecy capacity of the enhanced channel is the same as the original channel, as the noise variances for the legitimate receiver did not change at all for any of the “active” subchannels. Therefore, at least for the special case of the parallel Gaussian wiretap channel, an enhanced channel does always exist.

Carrying over to the general vector Gaussian wiretap channel, no information should be transmitted along any direction where the eavesdropper observes a stronger signal than the legitimate receiver. The effective channel for the eavesdropper is thus a degraded version of the effective channel for the legitimate receiver. (This observation was also made by Khisti and Wornell [1].) This is the basis underlying the existence of the enhanced channel for a general vector Gaussian wiretap channel.

Note that in characterizing the capacity region of the vector Gaussian broadcast channel (a canonical model for the multi-antenna broadcast channel), Weingarten et al. [12] enhanced each and every channel (by reducing the noise covariance matrices) from the transmitter to the receivers. In our argument, however, we only enhanced the channel for the legitimate receiver. (The channel for the eavesdropper did not change at all). This is due to the fact that in both arguments, the enhancement, \emph{a priori}, must increase the capacity (secrecy or regular) of the channel. (Otherwise, both arguments will break down.) Whereas reducing the noise covariances will benefit all the receivers and hence improve the capacity of the vector Gaussian broadcast channel, reducing the noise covariance matrix of the eavesdropper may compromise the security of the transmission scheme.
and hence lower the secrecy capacity of the vector Gaussian wiretap channel. This is the key difference between the channel enhancement argument here and that of Weingarten et al. [12] for the vector Gaussian broadcast channel.

A Proof of Inequality (17)

To prove inequality (17), it is equivalent to show that \( X_G^* \sim \mathcal{N}(0, K_x^*) \) is an optimal solution to the optimization problem

\[
\max_{f(X): \mathbb{E}[XX^t] \preceq S} [h(X + W_r) - h(X + W_e)]
\]

which would handle the Gaussianity and the covariance matrix issues in one shot. For that purpose, we shall prove that \( g(X) \leq g(X_G^*) \) where

\[
g(X) := h(X + W_r) - h(X + W_e)
\]

for any \( X \) such that \( \mathbb{E}[XX^t] \preceq S \).

For any \( X \) such that \( \mathbb{E}[XX^t] \preceq S \) and any \( \lambda \in [0, 1] \), let

\[
X_\lambda := \sqrt{1 - \lambda} X + \sqrt{\lambda} X_G^*
\]

where we assume that \( X \) and \( X_G^* \) are independent. By the de-Bruijn identity [5, Cha. 16.6],

\[
\frac{dg(X_\lambda)}{d\lambda} = \frac{1}{2(1 - \lambda)} \text{Tr} ((K_x^* + K_e) J(X_\lambda + W_r) - (K_x^* + K_e) J(X_\lambda + W_e))
\]

where \( J(X) \) denotes the Fisher information matrix of \( X \). Recalling the vector Fisher information inequality [14, Lemma 1]

\[
J(X_1 + X_2) \preceq AJ(X_1)A^t + (I - A)J(X_2)(I - A)^t
\]

for two independent random vectors \( X_1 \) and \( X_2 \) and letting

\[
A = (K_x^* + K_e)^{-1}(K_x^* + K_r),
\]

we have

\[
J(X_\lambda + W_r) \preceq A^{-1}(J(X_\lambda + W_r) - (I - A)J(W)(I - A)^t)A^{-t} = (K_x^* + K_r)^{-1}(K_x^* + K_e) J(X_\lambda + W_e)(K_x^* + K_e) - (K_e - K_r))(K_x^* + K_r)^{-1}
\]
where \( W \) is \( \mathcal{N}(0, K_e - K_r) \) and is independent of \((W_r, X, X^*_G)\). Substituting (31) into (28), we have

\[
\frac{dg(X_\lambda)}{d\lambda} \geq \frac{1}{2(1-\lambda)} \text{Tr} \left( (K^*_x + K_r)(J(X_\lambda + W_r)(K^*_x + K_r) - I)((K^*_x + K_r)^{-1} - (K^*_x + K_e)^{-1}) \right)
\]

\[
= \frac{1}{2(1-\lambda)} \text{Tr} \left( (K^*_x + K_r)(J(X_\lambda + W_r)(K^*_x + K_r) - I)M_2 \right)
\]

\[
\geq \frac{1}{2(1-\lambda)} \text{Tr} \left( (K^*_x + K_r)((S + K_r)^{-1}(K^*_x + K_r) - I)M_2 \right)
\]

\[
= \frac{1}{2(1-\lambda)} \text{Tr} \left( (K^*_x + K_r)(S + K_r)^{-1}(K^*_x - S)M_2 \right)
\]

\[
= 0
\]

where equalities (32) and (34) are due to the equations in (12), and inequality (33) is due to the well-known Cramér-Rao inequality

\[
J(X) \succeq \text{Cov}^{-1}(X)
\]

and the fact that \( \text{Cov}(X) \leq E[XX^t] \leq S \). That is, \( g(X_\lambda) \) is a monotonically nondecreasing function of \( \lambda \) in \([0, 1]\). We thus have

\[
g(X) = g(X_0) \leq g(X_1) = g(X^*_G).
\]

This completes the proof of inequality (17).

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