Beamforming Aided Interference Management with Improved Secrecy for Correlated Channels

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***Abstract*—This paper targets the joint optimization of the signal-to-interference-plus-noise ratio (SINR) and secrecy in wireless networks. Although the optimization of the SINR with beamforming in wireless networks is well known, the joint optimization of the secrecy and the SINR of the users is a new problem which gets a high relevance recently. The optimization problems investigated in this paper are based on the joint optimization of the beamforming vectors and transmit powers.**

This paper presents closed form solutions for two optimization approaches for a simple power control scenario with a single user and a single eavesdropper. Two approaches are distinguished: beamforming without artificial interference (AI) and beamforming with AI. For both approaches, this paper investigates a max–min based beamforming problem and a minimum eavesdropper SINR problem with an SINR constraint for the legitimate receiver.

***Index Terms*—Max-min beamforming, secrecy, power control.**

I. Introduction

Beamforming is a well investigated field regarding interference mitigation in a multiuser scenario [1], [2]. In addition to the interference minimization in multiuser networks, beamforming has drawn a lot of attention in networks with increased secrecy requirements. Here, a legitimate user Bob gets secret information from its legitimate transmitter Alice. A passive eavesdropper Eve jointly receives the signal transmitted by Alice. With beamforming the signal transmitted to Bob can be maximized while jointly minimizing the signal power received by the eavesdropper, Eve.

A. Related Work

Already in 1975, Wyner [3] observed that the capacity of a system consisting of a legitimate user Bob and an eavesdropper Eve, is the difference between the capacities of these two channels. This capacity is called the secrecy capacity. Using smart antennas, an improved secrecy capacity can be achieved with beamforming. Two beamforming approaches are investigated in the literature: the first approach only considers beamforming to increase the received signal power at the legitimate user while jointly reducing the received signal power at the eavesdropper. The authors in [4] investigate the problem of a maximized secrecy capacity such that the target secrecy capacity for a given secrecy outage probability is maximized. Authors in [5] investigate the Gaussian broadcast channel in the presence of a passive eavesdropper with assuming the presence of full channel state information (CSI) knowledge of all links. They show that the general multiple input multiple output (MIMO) rate maximization is non-convex, however the simplified multiple input single output (MISO) case can be solved with an efficient algorithm. The maximization of the relative signal-to-interference-plus-noise ratio (SINR), which is given by the ratio of the legitimate user's SINR divided by the eavesdropper SINR, is investigated in [6].

In addition to beamforming, the second approach additionally uses artificial interference (AI) to reduce the SINR of the eavesdropper. In [7], [8], an additional helping user (Hugo) generates interference for the eavesdropper. The authors show that zero forcing (ZF) is nearly optimal for high SNR. In [9]–[11], the authors investigate the power minimization problem (PMP). As in the case without secrecy, a minimized total transmit power for a given quality-of-service (QoS) constraint for the users is desired. Here additionally an SINR constraint for the eavesdropper is guaranteed as well. In [9], the authors consider minimization of Eve's SINR (rate) subject to an SINR constraint for Bob, and also a maximization of Bob's SINR given an eavesdropper SINR constraint. For both problems, convex semi-definite programming based reformulations are presented. Having multiple eavesdroppers, a max–min fair approach is also reasonable. The authors in [12] have proved that the max–min fair optimization of the secrecy capacity with beamforming has an equivalent semi-definite programming form with a rank-1 solution.

B. Contribution

In general it is diffcult to get channel state information of Eves channel, therefore, this paper considers beamforming approaches based on channel statistics. These statistics can be obtained based on a priori measurements of environment. This paper compares the two beamforming approaches (beamforming with AI and without AI) with two optimization problems: The first one is called max–min fair beamforming problem (MBP) approach where a joint maximization of the inverse eavesdropper SINR and the SINR of the legitimate user is desired. For the case without AI, the problem is proved to be equivalent to the relative SINR maximization, as presented in [6]. The second problem is called minimum eavesdropper SINR problem (MEP). Here, the SINR of the eavesdropper, given a QoS constraint for the legitimate user, is minimized.

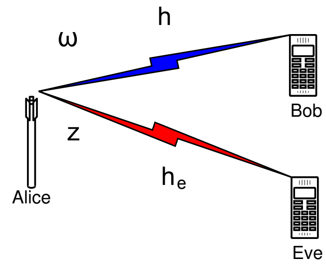

Fig. 1: Signal Model.

It is proved, that both problems are equivalent if the QoS of the MEP is equal to the optimal balanced SINR of the MBP. For both problems and both approaches, simple closed form solutions are derived and illustrated via numerical results.

C. Notation:

Lower case and upper case boldface symbols denote vectors and matrices, respectively. The conjugate transpose of a matrix $\mathbf{A}$ is denoted with $\mathbf{A}^H$ and $\mathbf{I}$ denotes the identity matrix.

II. Signal Model

The system consist of a single base station (Alice) with a smart antenna array of N_A correlated antenna elements, a legitimate receiver (Bob) with a single antenna and an unauthorized receiver (Eve) eavesdropping with a single antenna.

The channel vector between Alice (the BS) and Bob is denoted by $\mathbf{h} \in \mathbb{C}^{N_A \times 1}$. The linear precoding vector of BS is denoted by $\boldsymbol{\omega} = \sqrt{p}\mathbf{u}$, with the domains $\mathcal{U} = \{\mathbf{u} \in \mathbb{C}^{N_A \times 1} \; : \; ||\mathbf{u}|| = 1\}$ and $\mathcal{P} = \{p \in \mathbb{R} \; : \; p \geq 0\}$. The artificial interference vector is denoted by $\mathbf{z}$ with the domain $\mathcal{Z} = \{\mathbf{z} \in \mathbb{C}^{N_A \times 1} \; : \; ||\mathbf{z}|| = 1\}$. The thermal noise ν of the user Bob and Eve is assumed to be zero mean, Gaussian and circular symmetric with a variance of σ^2. Furthermore, the BS transmits a superposition of signals:

$$\mathbf{x} = \boldsymbol{\omega} s + \mathbf{z} f \tag{1}$$

with $\mathbb{E}\{|s|^2\} = 1$ and $\mathbb{E}\{|f|^2\} = 1$. Here the signal s corresponds to the useful information which is intended for Bob. The signal f is the artificial interference transmitted to Eve. The signal Bob receives is given by:

$$r = \mathbf{h}^H(\boldsymbol{\omega} s + \mathbf{z} f) + \nu. \tag{2}$$

With the definition of $\mathbf{R} = \mathbb{E}\{\mathbf{h}\mathbf{h}^H\}$ in the case of long-term channel state information (CSI) or $\mathbf{R} = \mathbf{h}\mathbf{h}^H$ in the case when instantaneous CSI is available, the SINR of the users is defined by:

$$\gamma(\boldsymbol{\omega}, \mathbf{z}) = \frac{\boldsymbol{\omega}^H \mathbf{R} \boldsymbol{\omega}}{\mathbf{z}^H \mathbf{R} \mathbf{z} + \sigma^2}. \tag{3}$$

The eavesdropper has the ability to receive the signals from every BS in the network. Consequently, the received signal of the eavesdropper is:

$$r_e = \mathbf{h}_e^H(\boldsymbol{\omega} s + \mathbf{z} f) + \nu. \tag{4}$$

The vector $\mathbf{h}_e \in \mathbb{C}^{N_A \times 1}$ denotes the channel between BS and the eavesdropper. Similar to the SINR of Bob, the SINR of Eve is given by:

$$\gamma_e(\boldsymbol{\omega}, \mathbf{z}) = \frac{\boldsymbol{\omega}^H \mathbf{R}_e \boldsymbol{\omega}}{\mathbf{z}^H \mathbf{R}_e \mathbf{z} + \sigma^2}. \tag{5}$$

Here, $\mathbf{R}_e = \mathbb{E}\{\mathbf{h}_e \mathbf{h}_e^H\}$ denotes the spatial correlation matrix of Eve in the case of long-term (CSI) or $\mathbf{R}_e = \mathbf{h}_e \mathbf{h}_e^H$ in the case when instantaneous CSI is available.

Two channel models can be distinguished: The first one is the so-called instantaneous far-field line-off-sight (LOS) scenario with a uniform linear array (ULA) at the BS as in [13]. With $\phi = \sin(\theta)$ the channel vectors of Bob and the eavesdropper are given by:

$$\mathbf{h}(\phi) = [1, e^{-j2\pi d\phi}, e^{-j2\pi d2\phi}, \ldots, e^{-j2\pi d(N_A-1)\phi}]^T, \tag{6}$$

where d is the normalized antenna spacing. The angle between the BS and Bob is denoted by θ and the angle between the BS and the eavesdropper is denoted with θ_e. Assuming channel knowledge of the directions θ and θ_e, the correlation matrices $\mathbf{R}(\phi) = \mathbf{h}(\phi)\mathbf{h}^H(\phi)$ and $\mathbf{R}(\phi_e) = \mathbf{h}(\phi_e)\mathbf{h}^H(\phi_e)$ are Toeplitz matrices. The second approach is based on long-term CSI. In this case, the channel matrix is calculated based on a superposition of N_p incoming waves in the case of a ULA as follows:

$$\mathbf{R} = \sum_{p=1}^{N_p} a_p \mathbf{h}(\phi_p)\mathbf{h}^H(\phi_p). \tag{7}$$

The scalar a_p denotes the path power.

III. Optimization Problems

This paper compares two optimization approaches based on beamforming:

- Beamforming, without AI ($\mathbf{z} = \mathbf{0}$) as defined in Eq. (2)
- Beamforming with AI as defined in Eq. (4)

For each of these two approaches, two optimization problems are investigated:

- **Max–min beamforming problem (MBP)** which desires the maximization of the worst SINR. To combine the two SINR constraints in the objective function, the maximization of the worst inverse SINR of the eavesdropper is desired.
- **Minimum eavesdropper SINR problem (MEP)** which desires the minimization of the eavesdropper SINR, while jointly guarantee a quality-of-service (QoS) SINR for Bob.

A. Beamforming without AI

This section considers the approach without AI ($\mathbf{z} = \mathbf{0}$). The MBP desires the maximization of the worst SINR. To achieve a minimization of the eavesdropper SINR, the inverse SINR should be maximized. The MBP can be stated as:

$$\gamma^* = \max_{\mathbf{u} \in \mathcal{U}, p \in \mathcal{P}} \; \min \{\gamma(p, \mathbf{u}), \; \gamma_e^{-1}(p, \mathbf{u})\}.$$

In the scenario without AI the SINR is reduced to a signal-to-noise ratio (SNR). First, we prove that the optimization of the SINR does not depend on the power control. To prove this property we first assume fixed beamforming vectors and we consider only the power p as a variable. With the effective channel of Bob given by $g = \mathbf{u}^H \mathbf{R} \mathbf{u}$ and the effective channel of the eavesdropper $h = \mathbf{u}^H \mathbf{R}_e \mathbf{u}$, the SNRs of Bob and Eve are given by:

$$\gamma(p) = p\frac{g}{\sigma^2}, \quad \gamma_e(p) = p\frac{h}{\sigma^2}, \tag{8}$$

respectively. The MBP can be stated as:

$$\hat{\gamma} = \max_{p \geq 0} \min \{\gamma(p), \frac{1}{\gamma_e(p)}\}. \tag{9}$$

With these assumptions, we can state the first proposition:

Proposition 1: The optimal balanced SNRs of problem (9) are the results:

$$\gamma_e(p) = \sqrt{\frac{h}{g}} \text{ and } \gamma(p) = \sqrt{\frac{g}{h}}. \tag{10}$$

Proof: The proof is straightforward. At the optimum, both SNRs are balanced, hence, $\gamma_e^{-1}(p) = \gamma(p)$. This results in the following quadratic equation:

$$p\frac{g}{\sigma^2} = \frac{\sigma^2}{p \cdot h} \Leftrightarrow p^2 = \frac{\sigma^4}{g \cdot h}.$$

The transmit power p is non-negative, $p \geq 0$, hence, the solution is $p = \frac{\sigma^2}{\sqrt{g \cdot h}}$. Inserting this solution in (8), the SNRs (10) are the results. ■

As we can see in this simple scenario, the SNRs of the eavesdropper and Bob only depend on the effective channel. Consequently, the transmit power p has no effect on the SNRs and, therefore, also on the secrecy.

As a consequence, we can decouple power control and beamforming optimization. Now we consider an optimization of the effective channels $g = \mathbf{u}^H \mathbf{R} \mathbf{u}$ and $h = \mathbf{u}^H \mathbf{R}_e \mathbf{u}$. This idea results in the second proposition:

Proposition 2: In the case of higher rank spatial correlation matrices, the optimal beamforming vector maximizing the SNR of Bob and minimizing the SNR of Eve is given by:

$$\mathbf{u}^* = \mathrm{argmax}_{\mathbf{u} \in \mathcal{U}} \, \mathbf{u}^H \mathbf{R}_e^{-1} \mathbf{R} \mathbf{u} \tag{11}$$

and the optimal SNR is then given by:

$$\gamma_e(\mathbf{u}^*) = \sqrt{\frac{1}{\lambda^*}} \text{ and } \gamma(\mathbf{u}^*) = \sqrt{\lambda^*} \tag{12}$$

where λ^* denotes the largest eigenvalue of $\mathbf{R}_e^{-1}\mathbf{R}$.

Proof: With (10) and $g = \mathbf{u}^H \mathbf{R} \mathbf{u}$ and $h = \mathbf{u}^H \mathbf{R}_e \mathbf{u}$, the optimal SNR as function of $\mathbf{u}$ is given by:

$$\gamma_e(\mathbf{u}) = \sqrt{\frac{\mathbf{u}^H \mathbf{R}_e \mathbf{u}}{\mathbf{u}^H \mathbf{R} \mathbf{u}}} \text{ and } \gamma(\mathbf{u}) = \sqrt{\frac{\mathbf{u}^H \mathbf{R} \mathbf{u}}{\mathbf{u}^H \mathbf{R}_e \mathbf{u}}}. \tag{13}$$

Now it is obvious that the joint maximization of $\gamma(\mathbf{u})$ and $\gamma_e^{-1}(\mathbf{u})$ can be achieved by finding the largest eigenvalue:

$$\lambda^* = \max_{\mathbf{u} \in \mathcal{U}} \mathbf{u}^H \mathbf{R}_e^{-1} \mathbf{R} \mathbf{u} \tag{14}$$

where $\mathbf{u}^*$ denotes the corresponding eigenvector. ■

A similar result for instantaneous MIMO channels is observed for the MEP in [14].

Observe, in the case $\theta = \theta_e$ and $d = d_e$, the SNR of Bob and the eavesdropper are the same due to $\mathbf{R} = \mathbf{R}_e \Rightarrow \lambda^* = 1$. This situation corresponds to the worst case, where Bob and Eve are at the same position.

Furthermore, observe that the MBP is also equivalent to the relative SINR maximization problem [6]:

$$\gamma^* = \max_{\mathbf{u} \in \mathcal{U}, p \in \mathcal{P}} \frac{\gamma(p, \mathbf{u})}{\gamma_e(p, \mathbf{u})} = \max_{\mathbf{u} \in \mathcal{U}, p \in \mathcal{P}} \frac{\mathbf{u}^H \mathbf{R} \mathbf{u}}{\mathbf{u}^H \mathbf{R}_e \mathbf{u}}. \tag{15}$$

This problem is optimally solved with the same beamforming vector as given in (11).

In a scenario with an eavesdropper, another optimization problem can be considered as well. We call this problem minimum eavesdropper SINR problem (MEP). This problem can be stated as follows:

$$\gamma_e^* = \min_{\mathbf{u} \in \mathcal{U}, p \in \mathcal{P}} \gamma_e(p, \mathbf{u}) \quad \text{s.t. } \gamma(p, \mathbf{u}) \geq \gamma_Q. \tag{16}$$

We will show that the MEP and the MBP are also related problems. In the simplified single user scenario with a fixed beamformer, the MEP can be stated as:

$$\hat{\gamma}_e = \min_{p \geq 0} \gamma_e(p) \quad \text{s.t. } \gamma(p) \geq \gamma_Q. \tag{17}$$

As for the MBP also for the MEP, the optimal SNR is given by a closed form solution:

Proposition 3: The minimal SNR of the eavesdropper in problem (17) is given by:

$$\gamma_e(p) = \frac{\gamma_Q \cdot h}{g} \tag{18}$$

Proof: The proof is as simple as the proof of Proposition 1. At the optimum, the SNR of Bob is $\gamma(p) = \gamma_Q$. Consequently,

$$\gamma(p) = \frac{p \cdot g}{\sigma^2} = \gamma_Q \tag{19}$$

holds. Hence, the optimal solution for p is $p = \frac{\gamma_Q \cdot \sigma^2}{g}$. Inserting p in the eavesdropper SNR of (8) results in (18). ■

Also for the MEP, we can observe that SNR only depends on the effective channels. In addition, there is also a dependency on the quality-of-service SNR γ_Q. Based on the previous observations we can see the equivalence of the MBP and MEP in the case both problem have the same feasible SINR $\gamma^* = \gamma_Q$.

B. Beamforming with Artificial Interference

Now AI is considered as an additional optimization variable. We again begin with the MBP:

$$\gamma^* = \max_{\mathbf{u} \in \mathcal{U}, p \in \mathcal{P}, \mathbf{z} \in \mathcal{Z}} \min \{\gamma(p, \mathbf{u}, \mathbf{z}), \gamma_e^{-1}(p, \mathbf{u}, \mathbf{z})\}.$$

Similar to the approach without AI, we first prove that we can decouple the optimization of p and and the beamforming vectors. Using the effective channels $g = \mathbf{u}^H \mathbf{R} \mathbf{u}$, $h = \mathbf{u}^H \mathbf{R}_e \mathbf{u}$, $q = \mathbf{z}^H \mathbf{R} \mathbf{z}$, and $r = \mathbf{z}^H \mathbf{R}_e \mathbf{z}$, SINRs of Bob and Eve are given by:

$$\gamma(p) = p\frac{g}{q + \sigma^2}, \quad \gamma_e(p) = p\frac{h}{r + \sigma^2}, \tag{20}$$

Then the MBP, can be stated as in (9). With these assumptions, we can state the following proposition corresponding to Proposition 1 in presence of AI:

Proposition 4: The optimal balanced SINRs of problem (9) with the SINRs (20) are:

$$\gamma_e(p) = \sqrt{\frac{(q+\sigma^2)\cdot h}{(r+\sigma^2)\cdot g}} \text{ and } \gamma(p) = \sqrt{\frac{(r+\sigma^2)\cdot g}{(q+\sigma^2)\cdot h}} \quad (21)$$

Proof: The proof is similar to the proof of Proposition 1. At the optimum, both SNRs are balanced, hence, $\gamma_e^{-1}(p) = \gamma(p)$. As in the proof of Proposition 1, the following quadratic equation

$$p\frac{g}{q+\sigma^2} = \frac{r+\sigma^2}{p\cdot h} \quad \Leftrightarrow \quad p^2 = \frac{(r+\sigma^2)\cdot(q+\sigma^2)}{g\cdot h}$$

results. Inserting the non-negative value of $p = \sqrt{\frac{(r+\sigma^2)\cdot(q+\sigma^2)}{g\cdot h}}$ in (20), the SINRs of (21) are the results. ■

Proposition 4 proves that the optimization of the SINRs can be decoupled from the optimization of the transmit power and the beamforming vectors. Hence, the equivalent of Proposition 2 in presence of AI can be formulated:

Proposition 5: In the case of higher rank spatial correlation matrices, the optimal beamforming vectors maximizing the SINR of Bob and minimizing the SINR of Eve is given by:

$$\mathbf{u}^* = \operatorname{argmax}_{\mathbf{u}\in\mathcal{U}} \mathbf{u}^H \mathbf{R}_e^{-1}\mathbf{R}\mathbf{u} \quad (22)$$

and

$$\mathbf{z}^* = \operatorname{argmax}_{\mathbf{z}\in\mathcal{Z}} \mathbf{z}^H(\mathbf{R}+\sigma^2\mathbf{I})^{-1}(\mathbf{R}_e+\sigma^2\mathbf{I})\mathbf{z} \quad (23)$$

and the optimal SINR is then given by:

$$\gamma_e(\mathbf{u}^*,\mathbf{z}^*) = \sqrt{\frac{1}{\lambda^*\mu^*}} \text{ and } \gamma(\mathbf{u}^*,\mathbf{z}^*) = \sqrt{\lambda^*\mu^*} \quad (24)$$

where λ^* denotes the largest eigenvalue of $\mathbf{R}_e^{-1}\mathbf{R}$ and μ^* denotes the largest eigenvalue of $(\mathbf{R}+\sigma^2\mathbf{I})^{-1}(\mathbf{R}_e+\sigma^2\mathbf{I})$

Proof: With (21) and the definitions of g, h, q, and r, the optimal SINR $\gamma(p,\mathbf{u},\mathbf{z}) = \gamma_e^{-1}(p,\mathbf{u},\mathbf{z})$ as function of $\mathbf{u}$ and $\mathbf{z}$ is given by:

$$\gamma(\mathbf{u},\mathbf{z}) = \sqrt{\frac{\mathbf{z}^H(\mathbf{R}_e+\sigma^2\mathbf{I})\mathbf{z}}{\mathbf{z}^H(\mathbf{R}+\sigma^2\mathbf{I})\mathbf{z}}\cdot\frac{\mathbf{u}^H\mathbf{R}\mathbf{u}}{\mathbf{u}^H\mathbf{R}_e\mathbf{u}}} \quad (25)$$

A joint maximization of $\gamma(p,\mathbf{u},\mathbf{z})$ and $\gamma_e^{-1}(p,\mathbf{u},\mathbf{z})$ can be achieved by finding the largest eigenvalues:

$$\lambda^* = \max_{\mathbf{u}\in\mathcal{U}} \mathbf{u}^H(\mathbf{R}_e)^{-1}\mathbf{R}\mathbf{u} \quad (26)$$

and

$$\mu^* = \max_{\mathbf{z}\in\mathcal{Z}} \mathbf{z}^H(\mathbf{R}+\sigma^2\mathbf{I})^{-1}(\mathbf{R}_e+\sigma^2\mathbf{I})\mathbf{z} \quad (27)$$

where $\mathbf{u}^*$ and $\mathbf{z}^*$ denote the corresponding eigenvectors. ■

The MEP can be also decoupled in a power and beamforming optimization. The MEP with power optimization is stated in (17). Similar to Proposition 3, we can formulate the following proposition.

Proposition 6: In the case of AI, the minimal SNR of the eavesdropper in Problem (17) is given by:

$$\gamma_e(p) = \gamma_Q\frac{(q+\sigma^2)\cdot h}{(r+\sigma^2)\cdot g}. \quad (28)$$

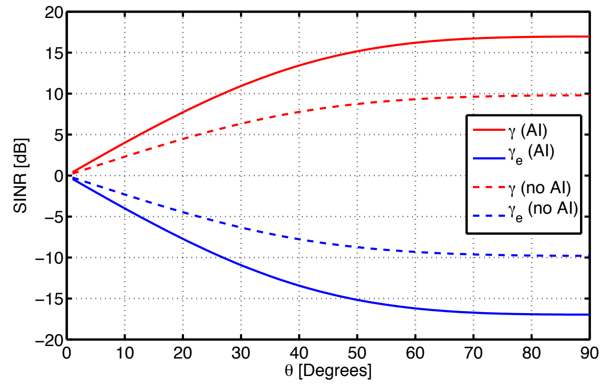

Fig. 2: MBP with and without AI: Numerical results of the SNR given in (13).

Proof: The proof is similar to the proof of Proposition 3. At the optimum, the SNR of Bob is $\gamma(p) = \gamma_Q$. Consequently,

$$\gamma(p) = \frac{p\cdot g}{q+\sigma^2} = \gamma_Q \quad (29)$$

holds. Hence, the optimal solution for p is $p = \frac{\gamma_Q\cdot(q+\sigma^2)}{g}$. Inserting p in Eve's SINR (20) results in (28). ■

IV. Numerical Results

To visualize the derived propositions, we present some numerical results based on different angles between Bob and Eve. The spatial correlation matrices have higher rank and are calculated based on (7). We assume a Laplacian power angular distribution [15] of the incoming paths powers a_p with a power angular deviation of 15°. The BS is equipped with a ULA with $N_A = 4$ antenna elements with an antenna spacing of $d = d_e = 1/2$. To simplify the investigations, we consider the approximation $\sigma^2 = 0.1$. This assumption is reasonable in the case when the interference is much larger than the noise level.

The dashed lines in Figure 2 show the SNR of Bob and the eavesdropper based on the MBP. Bob and the eavesdropper have the same distance to the BSs. The position of the eavesdropper is assumed to be fixed at $\theta_e = 0°$. The position of Bob varies from $\theta = 1°$ to $\theta = 90°$. As expected, the SNR of Bob γ is maximized when the angular distance is maximized. At $\theta = 0°$ the ratio between the SNRs becomes equal to one.

Figure 3 depicts the SNR of the eavesdropper based on the MEP for different values of γ_Q. The constant lines depict different levels of γ_Q. The larger γ_Q, the larger is also the SNR of the eavesdropper. As given in (18), the SNR of the eavesdropper grows proportionally with the γ_Q. The solid lines in Figure 2 depict the SINR of Bob and Eve when AI is considered as well. The separation of the SINRs is larger compared to the case without AI. The SINR of the MEP with AI is depicted in Figure 4. Also this figure shows a better reduction of Eve's SINR.

V. Discussion

Table I, presents a comparison of the different approaches derived in this paper. The MBP has the advantage that SINR

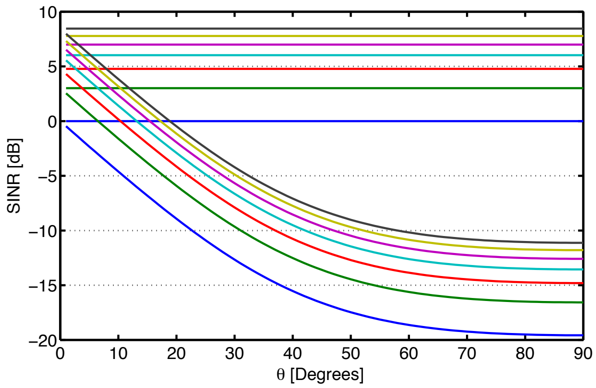

Fig. 3: MEP without AI: Numerical results of the SNR given in (18) for different values of $\gamma_Q \in \{1, 2, \ldots, 7\}$ in linear scale given by the dashed lines.

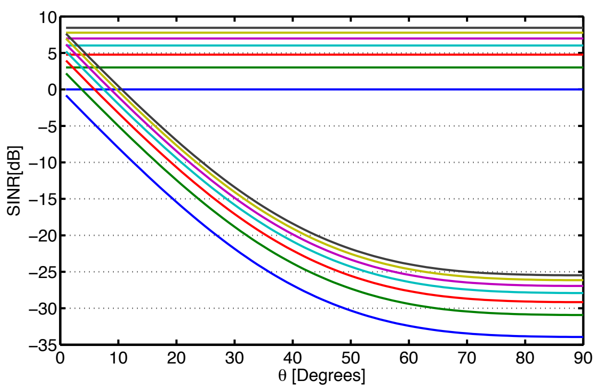

Fig. 4: MEP with AI: Numerical results of the SNR given in (28) for different values of $\gamma_Q \in \{1, 2, \ldots, 7\}$ given by the dashed lines.

TABLE I: Comparison of the four different approaches investigated in this paper.

	MBP	MEP
without AI	preserves secrecy $\gamma_e \leq 1$ $\gamma = \sqrt{\lambda^*}$ one eigenvalue problem	secrecy depends on γ_Q $\gamma = \gamma_Q$ one eigenvalue problem
with AI	preserves secrecy $\gamma_e \leq 1$ $\gamma = \sqrt{\lambda^* \mu^*}$ higher secrecy two eigenvalue problems	secrecy depends on γ_Q $\gamma = \gamma_Q$ higher secrecy two eigenvalue problems

of the eavesdropper is always $\gamma_e \leq 1$. This is not given for the MEP. For large values of γ_Q the SINR of the eavesdropper will be larger than 1 if the eavesdropper is close to Bob (in presence of spatially correlated channels). At the optimal position of Bob compared to the eavesdropper, the distance between the eavesdropper SINR γ_e and Bob's SINR γ is maximized. The approach with artificial interference has much better performance. This is due to the additional optimization variable $\mathbf{z}$. Comparing the SINRs of the two approaches, we can see that the SINR without artificial interference $\gamma = \sqrt{\lambda^*}$ is a factor $\sqrt{\mu^*}$ smaller than the SINR with artificial interference $\gamma_{AI} = \sqrt{\lambda^* \mu^*}$. As we have a transmit power given by, e.g., $p = \frac{\sigma^2}{\sqrt{g \cdot h}}$, large noise levels compared to $g \cdot h$ may result in high transmit powers. A simple constraint as $p = \frac{\sigma^2}{\sqrt{g \cdot h}} \leq P$ can be used to constrain the peak transmit power below some level. In our future research, we will investigate possible closed form solutions with additional power constraints at the base station. For a scenario with multiple users, methods based on convex solvers already exists. A future research topic could be the investigation of less complex iterative algorithms for the multi-user case.

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