

Sensing-Assisted Receivers for Resilient-By-Design 6G MU-MIMO Uplink

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Abstract—We address the resilience of future 6G MIMO communications by considering an uplink scenario where multiple legitimate transmitters try to communicate with a base station in the presence of an adversarial jammer. The jammer possesses full knowledge about the system and the physical parameters of the legitimate link, while the base station only knows the UL-channels and the angle-of-arrival (AoA) of the jamming signals. Furthermore, the legitimate transmitters are oblivious to the fact that jamming takes place, thus the burden of guaranteeing resilience falls on the receiver. For this case we derive one optimal jamming strategy that aims to minimize the rate of the strongest user and multiple receive strategies, one based on a lower bound on the achievable signal-to-interference-to-noise-ratio (SINR), one based on a zero-forcing (ZF) design, and one based on a minimum SINR constraint. Numerical studies show that the proposed anti-jamming approaches ensure that the sum rate of the system is much higher than without protection, even when the jammer has considerably more transmit power and even if the jamming signals come from the same direction as those of the legitimate users.

Index Terms—Worst-case jammer, Multiple-Input-Multiple-Output (MIMO), 6G, Joint communication and sensing (JCAS), Beamforming

I. INTRODUCTION

A. Motivation

While the first generations of mobile communications standards concerned themselves with increasing data-rates and connectivity, the latter generations focused on a wide array of use-cases and applications. With the currently deployed 5G standard, very high data rates, reliability, low latency and massive connectivity between a very large number of entities are made possible, enabling applications such as the Tactile Internet for businesses, virtual reality and advanced, remote-controlled robotics [1]. In the future 6G standard, data rates and time sensitivity orders of magnitude higher than what are currently available, as well as connectivity for all things and digital twins are envisioned [2].

One of the key drivers towards enabling this massive digital transformation is integrated, or joint communication and

sensing (JCAS) [3], which offers radio sensing services along with communications capabilities, all under a unified hardware platform [4]. With the emergence of the virtualization not only of data, but of whole physical objects at once, the question of trustworthiness becomes crucial [5], which comprises, among other things the resilience of a system.

While jamming can also be friendly [6], a malicious jammer, who has access to all physical and system parameters of the environment, such as communication protocols, signal processing, physical channels, etc. is considered. This is also known as *worst-case* or *smart jammer*. The legitimate entities on the other hand only have access to their own system and physical parameters, and have very limited knowledge about the adversarial entity. In [5] it was shown that in the classical communication setting (without sensing), the question whether a denial-of-service attack has taken place is undecidable on a Turing machine [7]. This means that the coding layer can not ensure resilience against such attacks at the resource allocation level, and that other coordination mechanisms, also known as common randomness (CR), are required [7]. In this paper, we explore how to embed sensing information into a system architecture, which needs to be resilient by design. Our main goal is to optimally leverage sensing information and the spatial structure of the radio channel in order to design transmit and receive filters which are resistant against worst-case jammers. Note that this approach might naturally be interpreted in the CR context, since the AoAs assure the coordination resources.

B. Related Work and Main Contributions

While anti-jamming is a widely studied subject, to our knowledge there are no works which address the problem of designing resilient transceivers against a jammer who employs his optimal strategy by leveraging sensing information and the spatial structure of the radio channel. In [8] the authors propose a database approach to nullifying signals coming from the jammer direction using massive planar arrays, and by only considering the jammer power and not the its transmit strategy. In [9] and [10], the authors use reinforcement-learning (RL) to optimize various system parameters under the simplifying assumption that the jammer transmits uniformly over all streams.

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The characterization of a worst-case jammer in the context of MIMO communications has been done in terms of the optimal jammer strategy, albeit without considering the spatial structure of the radio channel. The authors in [11] derive the optimal transmit and jammer strategies using knowledge of the transmitted symbols strategy at the jammer and show that under certain conditions, this does not affect jammer performance. In [12] the authors prove that there exists a lower bound on the achievable rate of communication between the legitimate party, which does not depend on the jammer setup. Furthermore, they characterize and give a closed form solution of the optimal jamming strategy in the so-called *jammer-dominant regime* while in [13] the authors derive the optimal jamming strategy in closed form, which minimizes the signal-to-interference-and-noise-ratio (SINR) at the legitimate receiver in a MIMO system. At last, in [14] the authors use game theoretical tools to approach the problem of optimal resource allocation in the MIMO multiple access (MAC) and broadcast channels (BC) under jammer conditions, and show that the Nash equilibria of the resulting games always exist.

The only link between the concept of jamming and joint communication and sensing (JCAS) we are aware of, are the works of [15] and [16], where the authors employ knowledge about an eavesdroppers location in order to send artificial noise in its direction, therefore increasing the secrecy rate. Thus, our contributions are as follows:

- We construct a communication model which exploits the spatial structure of the radio channel and sensing information for a multi-user MIMO MAC scenario.
- We propose an optimal jamming strategy which minimizes the achievable rate of the strongest user, thus being robust against Successive Interference Cancellation (SIC) [17].
- Next we propose anti-jamming receive filters at the BS which only use AoA information. The proposed designs are based on a lower bound on the individual per-stream rate, a zero-forcing, and a minimum SINR constraint respectively.
- We demonstrate by numerical experiments, that we can ensure constant, satisfactory performance regardless of the number of antennas at the jammer. We also demonstrate numerically that the achieved sum-rate mainly depends on the AoA of the jamming signals and on the jamming power, and that the proposed designs can ensure a non-zero sum rate even in the most extreme cases.

C. Notation

Throughout this paper we denote the sets of natural, real and complex numbers by \mathbb{N} , \mathbb{R} and \mathbb{C} , respectively. We use lower case letters for scalars x , bold lower-case letters for vectors \mathbf{x} and bold upper-case letters for matrices \mathbf{X} . We write sets as $\{x_i\}_{i=1}^S$, where $i \in \mathbb{N}$ is the index and S is the cardinality of the set. The hermitian transpose and inverse of a matrix \mathbf{X} are denoted by \mathbf{X}^\top , \mathbf{X}^H , and \mathbf{X}^{-1} , respectively. The trace, Frobenius norm and rank of a matrix \mathbf{X} are written as $\text{tr}(\mathbf{X})$, $\|\mathbf{X}\|_F$ and $\text{rank}(\mathbf{X})$. The symbol \succ denotes the semi-ordering

relationship on the cone of positive semi-definite matrices. We use $\|\mathbf{x}\|_2$ to denote the Euclidean norm of a vector and \mathbf{e}_k for the k -th canonical basis vector in \mathbb{C}^N . Here, \mathbf{I} denotes the identity matrix. By $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{C}_x)$ we say the random vector \mathbf{x} is a zero-mean, proper Gaussian random variable with covariance matrix \mathbf{C}_x , and by $\mathcal{U}(a, b)$ we denote the uniform distribution on the interval $[a, b] \in \mathbb{R}$. Lastly, the mutual information between the two random variables \mathbf{x} and \mathbf{y} is denoted as $I(\mathbf{x}; \mathbf{y})$ and the real part of $z \in \mathbb{C}^N$ as $\Re\{z\}$.

II. PRELIMINARIES

A. System Model

We assume a setup consisting of K legitimate transmitters, a legitimate receiver / base station (Bob) and jammer (Jimmy). The transmitters send their data streams $s_k \sim \mathcal{N}(0, 1)$ by applying precoding with $\mathbf{w}_k \in \mathbb{C}^{N_{A_k}}$ through N_{A_k} antennas. The precoding vectors \mathbf{w}_k satisfy the power constraint $\|\mathbf{w}_k\|_2^2 \leq P_{A_k}$. The resulting signals $\mathbf{x}_k = \mathbf{w}_k s_k$ propagate through the legitimate channels $\mathbf{H}_k \in \mathbb{C}^{N_B \times N_{A_k}}$ and arrive at Bob's N_B antennas, where we assume $N_B \geq K+1$. The signal is corrupted by white noise $\mathbf{n} \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I})$, as well as by the jammer signal $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{C}_z) \in \mathbb{C}^{N_J}$, which propagates through the channel $\mathbf{G} \in \mathbb{C}^{N_B \times N_J}$, and satisfies the power constraint $\text{tr}(\mathbf{C}_z) \leq P_J$. At last, Bob applies the equalizers $\mathbf{v}_k^\text{H} \in \mathbb{C}^{1 \times N_B}$ to build an estimate \hat{s}_k for each the transmitted streams s_k . More formally:

$$\mathbf{x}_k = \mathbf{w}_k s_k \quad (1)$$

$$\mathbf{y} = \sum_{k=1}^K \mathbf{H}_k \mathbf{x}_k + \mathbf{G} \mathbf{z} + \mathbf{n} \quad (2)$$

$$\hat{s}_k = \mathbf{v}_k^\text{H} \mathbf{y} = \mathbf{v}_k^\text{H} \left(\sum_{k=1}^K \mathbf{H}_k \mathbf{w}_k s_k \right) + \mathbf{v}_k^\text{H} \mathbf{G} \mathbf{z} + \mathbf{v}_k^\text{H} \mathbf{n} \quad (3)$$

The legitimate channels \mathbf{H}_k and the jammer channel \mathbf{G} are modelled as spatial beam-space channels, namely

$$\mathbf{H}_k = \sum_{l=1}^{L_{H_k}} b_{H_k, l} \mathbf{a}_B(\theta_{H_k, l}) \mathbf{a}_{A_k}(\psi_{H_k, l})^\text{H} \quad (4)$$

$$\mathbf{G} = \sum_{l=1}^{L_G} b_{G, l} \mathbf{a}_B(\theta_{G, l}) \mathbf{a}_J(\psi_{G, l})^\text{H}, \quad (5)$$

with L_{H_k} , L_G being the number of resolvable paths for each channel, \mathbf{a}_S , $S \in \{A, B, J\}$ the steering vectors, and $\theta_{\cdot, l}$, $\psi_{\cdot, l}$, $b_{\cdot, l}$ the angles of arrival, angles of departure and path gain, corresponding to the l -th resolvable path in each channel, respectively.

For simplicity of analysis, we assume a 2D geometry, and thus all parties employ uniform linear arrays (ULA), with the steering vector given by

$$\mathbf{a}_S(\theta) = \left[1 \quad e^{-j \frac{2\pi d}{\lambda_c} \cdot \sin \theta} \quad \dots \quad e^{-j \frac{2\pi d}{\lambda_c} \cdot (N-1) \sin \theta} \right]^\top \quad (6)$$

where λ_c , d and N denote the wavelength, element spacing, and the number of elements. Defining the matrices

$$\mathbf{A}_B(\boldsymbol{\theta}_G) = [\mathbf{a}_B(\theta_{G,1}) \ \dots \ \mathbf{a}_B(\theta_{G,L_G})] \quad (7)$$

$$\mathbf{A}_J(\boldsymbol{\psi}_G) = [\mathbf{a}_J(\psi_{G,1}) \ \dots \ \mathbf{a}_J(\psi_{G,L_G})] \quad (8)$$

$$\mathbf{B}_G = \text{diag}\{b_{G,l}\}_{l=1}^{L_G} \quad (9)$$

with $\mathbf{A}_B(\boldsymbol{\theta}_G) \in \mathbb{C}^{N_B \times L_G}$, $\mathbf{A}_J(\boldsymbol{\psi}_G) \in \mathbb{C}^{N_J \times L_G}$, $\mathbf{B}_G \in \mathbb{C}^{L_G \times L_G}$, the jammer channel \mathbf{G} becomes

$$\mathbf{G} = \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{B}_G \mathbf{A}_J(\boldsymbol{\psi}_G)^H. \quad (10)$$

B. Metrics

The achievable rates R_k^A for each of the K users under *no particular decoding order* at the BS and the per-stream achievable rates R_B^k are given by

$$R_k^A = I(\mathbf{y}; s_k) = \log(1 + \gamma_k^A) \quad (11)$$

$$R_k^B = I(\hat{s}_k; s_k) = \log(1 + \gamma_k^B), \quad (12)$$

with γ_k^A, γ_k^B as in equations 13 and 14. The achievable sum-rates R^A, R^B are then given by summing over all R_k^A 's and R_k^B 's respectively.

III. JAMMER MODEL

We now present the smart jammer model used throughout the paper. We assume the jammer has access to all system and physical parameters of all links, i.e. $\{\mathbf{w}_k, \mathbf{H}_k, \mathbf{v}_k\}_{k=1}^K, \mathbf{G}, \sigma^2$, but not to the transmitted symbols s_k , since it has been shown in [11] that knowledge about s does not increase jammer performance if $\{\mathbf{w}_k, \mathbf{H}_k\}_{k=1}^K$ are known. The next assumption is that the jammer has more antennas than all parties, i.e. $N_J \geq N_{A_k}, N_B \forall k$, as well as more transmit power than all transmitters $P_J \geq P_{A_k} \forall k$. Finally, we assume that the disturbing transmission takes place in the so-called *jammer-dominant regime*. This concept was rigorously formalized in [12], and roughly speaking, means that the jammer power is much higher than the noise power, i.e. $P_J \gg \sigma^2$.

The goal of the jammer is to minimize the sum-rate R^A of all transmitters under the power constraint P_J . In order to achieve this, we consider the inequality

$$R^A = \sum_{k=1}^K R_k^A \leq K \max_k R_k^A. \quad (15)$$

Thus, if the rate of the ‘‘strongest’’ user can be brought to 0, then the sum rate is also 0. Since \log is a monotonically increasing function, the problem can be cast as

$$\mathbf{C}_z^* = \arg \min_{\substack{\mathbf{C}_z \succeq \mathbf{0}, \mathbf{C}_z = \mathbf{C}_z^H \\ \text{tr}(\mathbf{C}_z) \leq P_J}} \max_k \gamma_k^A. \quad (16)$$

This is a convex optimization problem, since both the objective function¹ and the constraints are convex. Note that we do not have to consider the equalizer at the receiver, since $R_k^A \geq R_k^B \forall k$ by standard information theoretical arguments.

¹The maximum over a family of convex functions is itself convex, the function $\mathbf{x}^H \mathbf{B}^{-1} \mathbf{x}$ is convex in symmetric positive semidefinite \mathbf{B} [18].

Furthermore, note that this jamming strategy can be greatly simplified if Successive Interference Cancellation (SIC) [17] is used at the receiver, since in this case, only the rate of one user needs to be minimized, rendering the problem equivalent to that in [13]. In the following sections, we will see how to ensure protection over a wide range of channel conditions when dealing with a jammer employing the strategy presented in (16).

IV. RESILIENT RECEIVER DESIGN

A. General Considerations

We assume the legitimate receiver has perfect knowledge of the channels and signal processing $\{\mathbf{w}_k, \mathbf{H}_k\}_{k=1}^K$ at the transmitters, and only has access to the AoAs $\boldsymbol{\theta}_G = \{\theta_{G,l}\}_{l=1}^{L_G}$ of the impinging jammer signals. Furthermore, the legitimate transmitters do not know the communication is jammed, and do not cooperate with each other. That being said, we assume for simplicity of analysis that the transmitters employ singular value decomposition (SVD), namely

$$\mathbf{w}_k = \mathcal{V}_{\max}(\mathbf{H}_k), \quad (17)$$

where $\mathcal{V}_{\max}(\mathbf{H}_k)$ denotes the right-singular vector corresponding to the largest singular value of the matrix \mathbf{H}_k .

In the following, we will concentrate on the receiver and derive a bound on the individual per-stream rate R_k^B , which depends, up to a constant, solely on its setup. We will then use this lower bound in our designs.

Let $\mathbf{V}_k = \mathbf{v}_k \mathbf{v}_k^H$ and consider

$$\begin{aligned} \mathbf{v}_k^H (\mathbf{G} \mathbf{C}_z \mathbf{G}^H + \sigma^2 \mathbf{I}) \mathbf{v}_k &= \text{tr}((\mathbf{G} \mathbf{C}_z \mathbf{G}^H + \sigma^2 \mathbf{I}) \mathbf{V}_k) \\ &= \text{tr}(\mathbf{G} \mathbf{C}_z \mathbf{G}^H \mathbf{V}_k + \sigma^2 \mathbf{V}_k). \end{aligned} \quad (18)$$

Plugging in the expression in (10) and introducing the matrix $\mathbf{E} = \mathbf{B}_G \mathbf{A}_J(\boldsymbol{\psi}_G)^H \mathbf{C}_z^{1/2}$, we obtain for the first term inside the trace

$$\text{tr}(\mathbf{G} \mathbf{C}_z \mathbf{G}^H \mathbf{V}_k) = \text{tr}(\mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{E} \mathbf{E}^H \mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k) \quad (19)$$

$$= \text{tr}(\mathbf{E} \mathbf{E}^H \mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k \mathbf{A}_B(\boldsymbol{\theta}_G)) \quad (20)$$

$$\leq \|\mathbf{E}\|_F^2 \text{tr}(\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k \mathbf{A}_B(\boldsymbol{\theta}_G)) \quad (21)$$

$$\leq \eta \text{tr}(\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k \mathbf{A}_B(\boldsymbol{\theta}_G)), \quad (22)$$

with $\eta = P_J N_J L_G \|\mathbf{B}_G\|_F^2$. (20) follows from the commutativity of trace, (21) follows from the fact that $\text{tr}(\mathbf{A} \mathbf{B}) \leq \text{tr}(\mathbf{A}) \text{tr}(\mathbf{B})$ for \mathbf{A}, \mathbf{B} symmetric positive-semidefinite [19, Section 1], and lastly, (22) follows from applying the sub-multiplicativity of the Frobenius norm twice, and from equations (4) and (7), respectively. With the shorthands,

$$\mathbf{A}_k = \mathbf{H}_k \mathbf{w}_k \mathbf{w}_k^H \mathbf{H}_k^H \quad (23)$$

$$\mathbf{B}_k = \sum_{k' \neq k} \mathbf{H}_{k'} \mathbf{w}_{k'} \mathbf{w}_{k'}^H \mathbf{H}_{k'}^H + \sigma^2 \mathbf{I}, \quad (24)$$

we have

$$\gamma_k^B \geq \frac{\mathbf{v}_k^H \mathbf{A}_k \mathbf{v}_k}{\mathbf{v}_k^H (\mathbf{B}_k + \eta \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H) \mathbf{v}_k} \triangleq \tilde{\gamma}_k^B. \quad (25)$$

$$\gamma_k^A = \mathbf{w}_k^H \mathbf{H}_k^H \left(\sum_{k' \neq k} \mathbf{H}_{k'} \mathbf{w}_{k'} \mathbf{w}_{k'}^H \mathbf{H}_{k'}^H + \mathbf{G} \mathbf{C}_z \mathbf{G}^H + \sigma^2 \mathbf{I} \right)^{-1} \mathbf{H}_k \mathbf{w}_k \quad (13)$$

$$\gamma_k^B = \frac{\mathbf{v}_k^H \mathbf{H}_k \mathbf{w}_k \mathbf{w}_k^H \mathbf{H}_k^H \mathbf{v}_k}{\mathbf{v}_k^H \left(\sum_{k' \neq k} \mathbf{H}_{k'} \mathbf{w}_{k'} \mathbf{w}_{k'}^H \mathbf{H}_{k'}^H + \mathbf{G} \mathbf{C}_z \mathbf{G}^H + \sigma^2 \mathbf{I} \right) \mathbf{v}_k} \quad (14)$$

We note that equality in (25) is achieved if $P_J = 0$ (no jammer) or if $\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k = \mathbf{0}$, i.e. equalizer \mathbf{v}_k lies in a subspace orthogonal to the array manifold $\mathbf{A}_B(\boldsymbol{\theta}_G)$.

We note that aside from η , all other terms in (25) are known at the receiver. In the jammer-dominant regime the term $\eta \text{tr}(\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k \mathbf{A}_B(\boldsymbol{\theta}_G))$ is much greater than σ^2 (since it scales linearly in P_J and N_J), effectively dominating the influence of the noise.

B. Closed-Form Design

The receivers' goal is to ensure reliable communication for all uplink participants, i.e. we are interested in maximizing the individual per-stream SINRs γ_k^B or at least ensure a certain quality of service (QoS), e.g. the γ_k^B 's lie above a given threshold γ_0 .

The maximization of the lower bound in Eq. (25) is a Rayleigh quotient maximization problem with the standard solution being given by:

$$\mathbf{v}_k = (\mathbf{B}_k + \eta \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H)^{-1} \mathbf{H}_k \mathbf{w}_k \quad (26)$$

for all $k = 1, \dots, K$. This is the most simple way to leverage AoA information at the receiver, since the solution is given in closed form and computationally tractable, since $\mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H$ can be easily computed without matrix multiplications by only considering the phase shifts between the impinging jamming signals.

Note, that the resulting filter still depends on η , which in general is not available at the receiver. The most easy way to address this problem is to consider η as a hyperparameter which controls how much the jamming signals are suppressed. Indeed, this is justified by the fact that in the jammer-dominant regime, the contribution of the noise variance σ^2 is small compared to the one of the jammer, i.e. $\mathbf{v}_k^H (\eta \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H + \sigma^2 \mathbf{I}) \mathbf{v}_k \approx \eta \mathbf{v}_k^H \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{v}_k$. In the following, we will propose other methods to overcome this dependency.

C. Zero Forcing Design

As it can be seen in Section IV-B, the main contribution to the jamming signals is given by the term

$$\beta_k = \|\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{v}_k\|_2^2 \quad (27)$$

which can be naturally interpreted as the receive beampattern of the receiver antenna array [20]. This indicates how much the signals coming from the jammer direction are emphasized, thus the anti-jamming criterion can be formalized as

a beampattern minimization problem in the same spirit as [15], [21], [22]. Furthermore, a natural way to ensure good per-stream SINRs for all users is to remove the interference, which can be realized with a zero-forcing (ZF) design. Thus, the beampattern minimization problem under ZF constraint can be formulated analogously to [21] as

$$\min_{\mathbf{v}_k} \sum_{k=1, \dots, K} \beta_k \quad \text{s.t.} \quad \mathbf{P}^H \mathbf{v}_k = \mathbf{e}_k \quad \forall k \quad (28)$$

where we defined

$$\mathbf{P} = [\mathbf{H}_1 \mathbf{w}_1 \quad \dots \quad \mathbf{H}_K \mathbf{w}_K] \in \mathbb{C}^{N_B \times K} \quad (29)$$

and \mathbf{e}_k is k -th standard basis vector in \mathbb{R}^K . Note that this is a convex optimization problem easily solvable in polynomial time.

Furthermore, if the matrix $\mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H$ has full-rank, we can also give an analytic solution. Letting $\mathbf{X} = \mathbf{A}_B(\boldsymbol{\theta}_G) \mathbf{A}_B(\boldsymbol{\theta}_G)^H$, we construct the Lagrangian

$$\mathcal{L}(\mathbf{v}_k, \boldsymbol{\mu}_k) = \sum_{k=1}^K \mathbf{v}_k^H \mathbf{X} \mathbf{v}_k + 2 \Re \{ \boldsymbol{\mu}_k^H (\mathbf{P}^H \mathbf{v}_k - \mathbf{e}_k) \} \quad (30)$$

where $\boldsymbol{\mu}_k \in \mathbb{C}^K$ are the Lagrange multipliers. Since the ZF-constraint is an equality constraint, the Karush-Kuhn-Tucker conditions are both necessary and sufficient. Computing the gradients wrt. \mathbf{v}_k and $\boldsymbol{\mu}_k$, setting them to $\mathbf{0}$, and solving for \mathbf{v}_k , we obtain

$$\mathbf{v}_k = \mathbf{X}^{-1} \mathbf{P} (\mathbf{P}^H \mathbf{X}^{-1} \mathbf{P})^{-1} \mathbf{e}_k \quad (31)$$

By standard linear algebra \mathbf{X} has full rank iff $L_G \geq N_B$, which might pose a problem if the propagation channel of the jammer shows $L_G < N_B$ dominant paths. In that case, one can easily "pad" the resolved AoAs $\boldsymbol{\theta}_G$ with a set of different angles $\{\phi_{G,l}\}_{l=1}^{N_B - L_G}$ thus enlarging the grid over which the beampattern should be minimized. This idea can be naturally extended to the designs considered in Sections IV-B and IV-D.

D. Minimum SINR Design

Another way to approach this problem is to minimize the influence of the jamming signals, while ensuring a minimum SINR γ_0 in the jammer-free case. Using this method one can address the disadvantages ZF-filters generally have in the low SNR regime, i.e. $\sigma^2 \gg 0$. Rewriting the beampattern β_k as

$$\beta_k = \|\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{v}_k\|_2^2 = \text{tr}(\mathbf{A}_B(\boldsymbol{\theta}_G)^H \mathbf{V}_k \mathbf{A}_B(\boldsymbol{\theta}_G)) \quad (32)$$

we cast the resulting problem as

$$\min_{\substack{\mathbf{V}_k \succeq \mathbf{0} \\ \text{rank}(\mathbf{V}_k)=1 \\ k=1, \dots, K}} \sum_{k=1}^K \beta_k \quad \text{s.t.} \quad \frac{\text{tr}(\mathbf{A}_k \mathbf{V}_k)}{\text{tr}(\mathbf{B}_k \mathbf{V}_k)} \geq \gamma_0 \quad (33)$$

with $\mathbf{V}_k = \mathbf{v}_k \mathbf{v}_k^H$ as before and \mathbf{A}_k and \mathbf{B}_k as in equations (23) and (24). Note that this problem is non-convex due to the rank-1 constraint on \mathbf{V}_k . In order to efficiently solve this problem, we apply semidefinite relaxation [23], i.e. we relax the rank-1 constraint, solve the resulting convex problem and recover the solution via eigenvalue decomposition (EVD).

V. NUMERICAL RESULTS

A. Methodology

In this section we present the performance of the proposed designs with respect to the jammer setup and channel conditions. To this end, we consider three parameters, namely the number of antennas at the jammer N_J , the power budget of the jammer P_J , and the AoAs θ_G of the impinging signals. We shall compare the sum-rates obtained by the proposed designs with the sum-rates in the jammer-free case, as well as in the case when the parties do not ensure any jammer protection. We consider a setup of $K = 3$ users, each with $N_{A_k} = 8$ and $P_{A_k} = 5$ dBm. The number of antennas at the legitimate transmitter N_B is kept fixed at 16, and the noise variance $\sigma^2 = -10$ dB. In order to generate the channel matrices, we draw all path gains and AoDs in (4) randomly from $\mathcal{N}(0, 1)$ and $\mathcal{U}(-5^\circ, 5^\circ)$. The AoAs are generated as $\theta_{G,l} = \theta_J + \phi_l$ and $\theta_{H_k,l} = \theta_{A_k} + \omega_l$, with ϕ_l and ω_l drawn i.i.d from $\mathcal{U}(-5^\circ, 5^\circ)$, and $\theta_{A_k} = \{-10^\circ, 0^\circ, 10^\circ\}$ from each other. The direction dependency of the channels are then characterized by the central AoA θ_J of the impinging jamming signal.

B. Simulation Studies

We first start by assessing the influence of the number of antennas at the jammer on the communication quality. To this end, we vary the number of antennas at the jammer N_J and average the computed sum-rates over θ_J and P_J . We first observe that the obtained sum rates are independent of the number of antennas at the jammer, since the performance curves remain relatively flat along the whole range. All of the proposed designs offer a much higher rate than in the cases without protection, with a minimum gain of 10 bits/s/Hz. In terms of performance ranking, the ZF-based design from equation (28) (denoted as ‘‘ZF’’ in Figures 1-3) performs best, followed by the optimal analytic filter based on the surrogate objective in equation (26) (‘‘Analytic’’ in Figures 1-3). The filter based on the minimum QoS (Equation (33)), denoted ‘‘MinSINR’’ in the plots, comes last.

We attribute this ranking to the fact that the filters ‘‘Analytic’’ and ‘‘MinSINR’’ are much more sensitive to the jamming power, since the former is coupled to it by the constant η , and the latter is based on an objective, that should ensure a minimum SINR at all times. This might not be fully-possible when jamming powers are high. In order to test this conjecture,

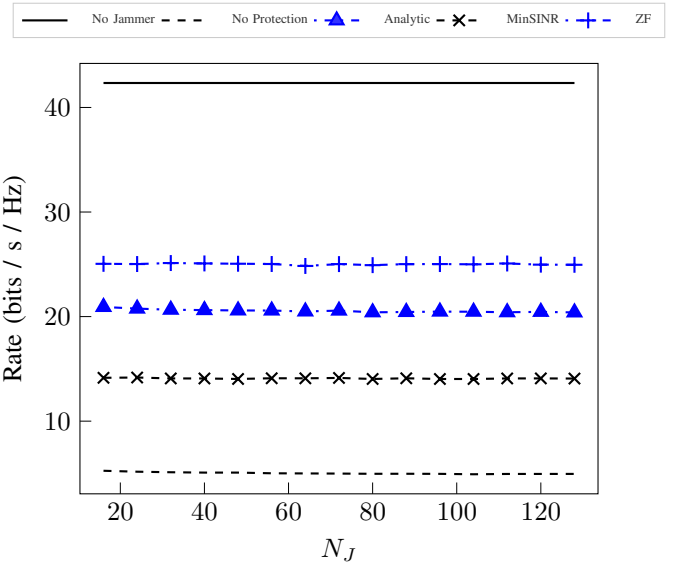


Fig. 1. Averaged sum-rates for different number of antennas at the jammer, $\gamma_0 = 20$ dB, $\eta = 1$.

we vary the jammer power P_J and average the computed sum-rates over θ_J and N_J . Indeed, while the filters based on the minimum SINR criterion and analytic formula decline sharply over the studied range, the filter based on the ZF criterion stays approximately constant over the whole range, only declining for high jammer powers.

Finally, we plot the performance of the proposed designs with respects to the AoA θ_J of the impinging jamming signals in Figure 3. Note, that the AoAs of the users are marked with a vertical, red line. We observe that the sum-rate decreases as the AoAs of the jamming signals become similar to those of the legitimate parties. We furthermore observe, that the jammer can not drive the sum-rate to 0 in the studied configuration. In terms of performance, the filter based on the analytic formula shows slightly better performance, than the ZF approach, in the case that the jamming and legitimate AoAs are similar.

VI. CONCLUSIONS

In this work, we derived a communication model which exploits the physical structure of the MIMO-MAC in the context of anti-jamming. We derived one optimal strategy at the jammer, which seeks to minimize the rate of the strongest user. We furthermore proposed an array of methods for protection against this worst-case jammer, possessing a far more powerful setup than the legitimate parties. We have shown experimentally, that we can achieve a non-zero sum-rate even if the jamming and legitimate signals come from roughly the same directions, and even if the jammer transmits with significantly more power. We conclude, that resilience can not be fully guaranteed by only using the spatial dimension of communication. Thus, our future work will be dedicated to the design of optimal signaling and frame structures, as well as to the study of optimal jamming strategies in these cases.

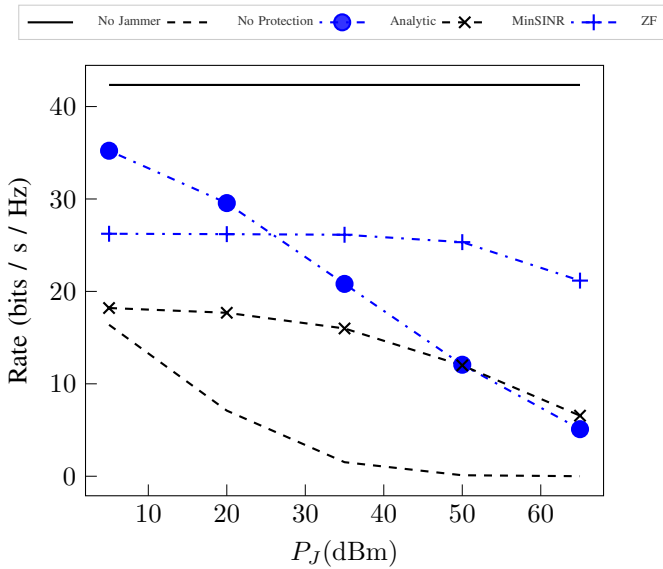


Fig. 2. Averaged sum-rates for different jammer powers, $\gamma_0 = 20\text{dB}$, $\eta = 1$.

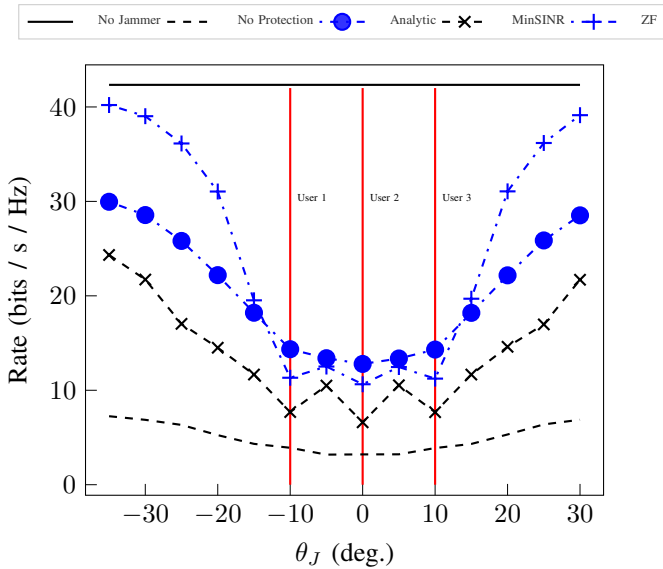


Fig. 3. Averaged sum-rates for different directions of arrival, $\gamma_0 = 20\text{dB}$, $\eta = 1$.

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