Leakage Subspace Precoding for Physical Layer Security in Multi-User XL-MIMO Systems

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Abstract—We investigate the achievable secrecy sum-rate in a multi-user XL-MIMO system, on which user distances to the base station become comparable to the antenna array dimensions. We show that the consideration of spherical-wavefront propagation inherent to these set-ups is beneficial for physical-layer security, as it provides immunity against eavesdroppers located in similar angular directions that would otherwise prevent secure communication under classical planar-wavefront propagation. A leakage subspace precoding strategy is also proposed for joint secure precoding and user scheduling, which allows to improve the secrecy sum-rate compared to conventional zero-forcing based strategies, under different eavesdropper collusion strategies.

Index Terms—Antenna array, XL-MIMO, near-field, physical layer security, secrecy sum-rate, eavesdroppers, scheduling.

I. INTRODUCTION

Extra-large aperture arrays (ELAs) or extra-large (XL) multiple-input multiple-output (MIMO) systems are the natural evolution of massive MIMO systems [1], bringing the opportunity to deploy base stations (BSs) with an even larger number of antenna elements to serve a larger set of users. Since antenna sizes in XL-MIMO deployments become comparable to user distances, new channel features that differ from classical planar-wavefront (PW) [2,3] and stationarity [4] assumptions have to be incorporated into the precoding design. One remarkable feature that arises when assuming spherical-wavefront (SW) propagation is the possibility of separating users in the spatial domain using both the angular direction and the distance with respect to the BS [5].

In the roadmap to defining 6G technology, several new use cases that enhance data security are being proposed [6], and physical layer security (PLS) is identified as a top contender to enable these secure features [7]. The literature of PLS is rich when assuming conventional multi-user MIMO settings [8,9]. Different strategies have been proposed for secure precoding design [10] and user scheduling [11] in massive MIMO set-ups, noting that the use of artificial noise may not always be helpful to improve the secrecy rates [12]. However, the impact of the inherent channel characteristics of XL-MIMO systems on PLS have not been addressed before, to the best of our knowledge. Hence, in this work we seek to find answers to two key questions: (i) how does SW propagation impact the achievable secrecy performance in XL-MIMO systems? (ii) how can user scheduling be improved when incorporating security constraints into the XL-MIMO set-up? We show that the extra flexibility arising when considering SW propagation can be leveraged to reduce information leakage to eavesdroppers. Thus, if the BS successfully exploits this additional degree of freedom, the achievable secrecy sum-rate substantially increases compared to the conventional PW assumption. To that end, we propose a novel joint scheduling and precoding scheme that improves the system secure performance compared to state-of-the-art solutions.

Notation: Throughout the text, sets are represented with calligraphic font, e.g., $\mathcal{C}$, whereas $|\mathcal{C}|$ denotes the cardinality of a set; uppercase and lowercase bold letters denote matrices and vectors, respectively; $\mathcal{N}_C(\cdot,\cdot)$ is the circularly symmetric complex Gaussian distribution; $\mathbb{C}$ is the set of complex numbers; diag$(\mathbf{x})$ is a diagonal matrix with the diagonal given by $\mathbf{x}$; span$(\mathcal{S})$ is the span of a set of vectors; $\cap$ and $\subseteq$ are the intersection and subset operators, respectively; $(\cdot)^\dagger$ denotes transpose; $(\cdot)^H$ is the Hermitian transpose; $\|\cdot\|_{\max}$ denotes max$\{\cdot,0\}$, where max represents the maximum value operator; argmax$\ f(z)$ denotes the value of $z$ that maximizes the function $f(\cdot)$.

II. SYSTEM MODEL

Let us consider a general downlink (DL) scenario, where a BS equipped with an XL antenna array with $M \gg 1$ elements gives service to a set $\mathcal{U}$ of single-antenna users, with $|\mathcal{U}| = K$. We assume an uniform linear array (ULA) as the antenna arrangement for the BS, which is placed at the origin of a 2-D plane and deployed along the $y$-axis. The BS operates in two modes [13]: in normal mode, channel state information (CSI) for all $K$ users is acquired in an uplink (UL) phase, which is then used to serve the DL users according to some sum-rate criterion [14]; in secure mode, a set $\mathcal{B}$ of legitimate users (i.e., Bobs) with $|\mathcal{B}| = K_B$ is served according to some secrecy sum-rate criterion, whereas the remaining set of users $\mathcal{V}$, with $|\mathcal{V}| = K_E = K - K_B$, are considered as potential eavesdroppers (i.e., Eves). The data intended to each legitimate receiver potentially experiences an amount of...
information leakage, which may be used by the eavesdroppers to compromise the transmission [8].

The distance between a given user, indexed by \( k \), and the \( m \)-th element of the antenna array is defined as:

\[
r_{k,m} = r_k \sqrt{1 - 2md_k \sin \theta_k + d_k^2 \lambda^2}, \quad m \in \left[ -\frac{M}{2}, \frac{M}{2} \right],
\]

where \( d_k \) is determined by the separation between two consecutive antenna elements, \( d = \frac{\lambda}{2} \), with \( \lambda \) being the wavelength. From (1), we obtain the array response vector for each user as follows

\[
\mathbf{a}_k = [a_1(r_k, \theta_k), a_2(r_k, \theta_k), \ldots, a_M(r_k, \theta_k)]^T,
\]

where the \( m \)-th element of the vector is expressed, depending on whether a spherical or a planar propagation model is assumed, as

\[
a_{SW}^m(r_k, \theta_k) = \sqrt{\frac{\pi}{r_{k,m}}} e^{-\frac{2\pi}{r_{k,m}} r_{k,m}},
\]

(3) and

\[
a_{PW}^m(r_k, \theta_k) = \sqrt{\frac{\pi}{r_k}} e^{-\frac{2\pi}{r_k} r_k} e^{-2\pi m \sin \theta_k},
\]

(4) respectively, and \( \beta_0 \) denotes the channel power at the reference distance \( r_{ref} = 1 \) m [3].

During the DL transmission in secure mode, the BS sends the data symbols \( s_k \sim \mathcal{C}(0, 1) \) to each legitimate user \( k \in \mathcal{B} \), by adapting the transmitted signal \( \mathbf{x} \) to the instantaneous channel state acquired in normal mode operation through the beamforming matrix \( \mathbf{W} \in \mathbb{C}^{M \times K_0} \), where we define the \( k \)-th column as \( \mathbf{w}_k \), with \( \| \mathbf{w}_k \| = 1 \), \( \forall k \in \mathcal{B} \). Therefore, it follows that the transmitted signal is \( \mathbf{x} = \sum_{k \in \mathcal{B}} p_k \mathbf{w}_k s_k \), where \( p_k \) are the power allocation scale factors such that \( P_{TX} = \sum_{k \in \mathcal{B}} p_k \), with \( P_{TX} \) the BS transmit power.

The received signal \( y_k \) for each legitimate user can be expressed in terms of the previously defined parameters as

\[
y_k = \sqrt{p_k s_k} \mathbf{w}_k^H \mathbf{a}_k + \sum_{j \neq k \in \mathcal{B}} \sqrt{p_j} s_j \mathbf{w}_j^H \mathbf{a}_k + n_k,
\]

(5) where the first term in (5) is the desired signal for the legitimate user, the second one represents the inter-user interference (IUI) due to legitimate users other than \( k \) being served simultaneously, and \( n_k \sim \mathcal{C}(0, \sigma_w^2) \) is the additive white Gaussian noise (AWGN). The signal-to-interference-plus-noise ratio (SINR) for the legitimate users is defined as [15]

\[
\text{SINR}_k = \frac{p_k \mathbf{w}_k^H \mathbf{a}_k^2}{\sigma_w^2 + \sum_{j \neq k \in \mathcal{B}} p_j \mathbf{w}_j^H \mathbf{a}_k^2}.
\]

Now, the legitimate symbols also reach the remaining users \( v \in \mathcal{V} \). From the point of view of these users (acting as eavesdroppers), such received signals are information leakage for the message \( s_k \), not interference. Therefore, a leakage-to-interference-plus-noise ratio (LINR) can be defined as \( \text{LINR}_k(v) = \frac{p_k \mathbf{w}_k^H a_k^2}{\sigma_c^2} \), which can be seen as the SINR associated to the message \( s_k \) at the \( v \)-th eavesdropper. As in [8], we assume the worst-case scenario on which the eavesdroppers have the ability to separate the \( k \) symbols (either by means of collusion, or in a genie-aided fashion).

We consider two practical scenarios for eavesdropping: (i) total collusion (TC), on which all eavesdroppers \( v \in \mathcal{V} \) collaborate into jointly decoding the message targeted to user \( k \); (ii) partial collusion (PC), on which only the eavesdroppers in the vicinity of user \( k \) are able to collude, i.e., \( v \in \mathcal{E}_k \), where \( \mathcal{E}_k \) is the set of colluding clustered eavesdroppers for user \( k \). Hence, the overall LINR is expressed as [9]

\[
\text{LINR}^\text{TC/PC}_k = \sum_{v \in \mathcal{V}/\mathcal{E}_k} \frac{p_k |\mathbf{w}_k^H \mathbf{a}_v|^2}{\sigma^2_w}.
\]

The rate of secure information is measured by the secrecy sum-rate, which is given from (6) and (7) as follows [8, 16]:

\[
R_s = \sum_{k \in \mathcal{B}} R_{s,k} = \sum_{k \in \mathcal{B}} \log_2 \left[ \frac{1 + \text{SINR}_k}{1 + \text{LINR}^\text{TC/PC}_k} \right] +.
\]

III. USER SCHEDULING AND PRECODING DESIGN

The aim is to maximize the secrecy sum-rate in (8) subject to the power constraint, i.e.,

\[
\text{argmax}_{\{p_k, p_{k,j}\}} \quad R_s \quad \text{s.t.} \quad \sum_{k \in \mathcal{B}} p_k \leq P_{TX}.
\]

We note from (6) and (7) that the achievable secrecy sum-rate is limited by the interference caused by legitimate users, either because it decreases the SINR of legitimate users, or because it increases the LINR of eavesdroppers. In the XL-MIMO regime, it is known that IUI (and hence information leakage) can be palliated not only by separating users in the angular domain (i.e., through \( \theta_k \)), but also in the distance domain even for users in the same direction [3]. Thus, this new degree of freedom (DoF) for interference and leakage reduction must be considered in order to jointly design the precoder and scheduling for PLS purposes.

There are key differences between conventional joint scheduling and precoding designs [14, 15], and their secure counterparts targeting a secrecy sum-rate maximization as the ones here addressed: specifically, (i) the classical sum-rate metric is simpler, (ii) only users selected by the scheduling procedure are considered to compute IUI, and (iii) information leakage to unscheduled users (i.e., Eves) is ignored. In the sequel, we describe a Leakage Subspace Precoding (LSP) approach for secure joint scheduling and precoding in this scenario, considering two collusion strategies for the eavesdroppers. An schematic view of the proposed scheduling and precoding method is given in Alg. [1] Moreover, the particularities to address both collusion strategies are detailed in the following.

1) TC scenario. This case corresponds to the conventional worst-case collusion where all the eavesdroppers share information to decode data of the legitimate users.

According to the LINR definition in (7), to avoid information leakage we propose to define a leakage subspace \( \mathcal{L} \), spanned by the channel vectors of the eavesdroppers,
i.e., \( \mathbb{L} = \text{span}(a_{v_1}, a_{v_2}, \ldots, a_{v_{|E_k|}}) \). Now, if the precoders associated to each legitimate user belong to the orthogonal subspace \( \mathbb{L}^\perp \), we ensure that \( \text{LINR}_{\text{TC}} = 0 \) in (8). Under this condition, it is simpler to decide which legitimate users will be allocated power.

The iterative procedure starts by setting an initial priority for each of the legitimate users \( q_k^{(0)} \), \( \forall k \in B \), computed as \( q_k^{(0)} = \| \Pi a_k \| \), where \( \Pi \) is the orthogonal projector into the subspace \( \mathbb{L}^\perp \). Next, similar to [15], we start an iterative procedure such that at the \( i \)-th iteration the user with higher priority, i.e.,

\[
k^{(i)} = \arg \max_{k \in B} q_k^{(i)}
\]

is chosen as a candidate to receive a certain amount of the available power budget \( P_{\text{TX}} \). To verify whether including the candidate user \( k^{(i)} \) increases the performance metric (8), we compute TC-zero-forcing (ZF) precoders for the set of users, \( S^{(i)} \subseteq B \), comprising the previously selected users at iteration \( i \) plus the candidate user \( k^{(i)} \) as

\[
[\omega_{k^{(1)}}, \ldots, \omega_{k^{(i)}}] = \Pi^* (A^{(i)} H (\Pi A^{(i)} H)^{-1}),
\]

where

\[
A^{(i)} = [a_{k^{(1)}}, a_{k^{(2)}}, \ldots, a_{k^{(i)}}]^T, \quad k \in S^{(i)}.
\]

Note that the projector \( \Pi \) is included in the computation of the TC-ZF precoders. Now, for \( k \in S^{(i)} \) we denote by \( S^{(i),k} = \text{span}(a_{j_1}, a_{j_2}, \ldots, a_{j_{i-1}}) \) the subspace spanned by the channels of the \( i-1 \) legitimate users in \( S^{(i)} \), with \( j_1, \ldots, j_{i-1} \neq k \). Hence, the feasible subspace for user \( k \) precoding is given by \( (S^{(i),k})^\perp \cap \mathbb{L}^\perp \). As the spatial characteristics of the channels strongly depend on the propagation model [3], the limitations on the available DoF for precoding design are different in SW and PW models. In particular, the additional DoF provided by the distance in the SW model [3] offers additional flexibility in the precoder design. Finally, the precoders for each of the selected legitimate users is \( w_k = \omega_k / \| \omega_k \| \), \( \forall k \in S^{(i)} \) and the power allocation \( P \) is chosen according to conventional waterfilling procedure [15], with \( P_{\text{TX}} = \sum_{k \in S^{(i)}} p_k \). This power allocation is optimal for (8) as the precoder design in (11) ensures no information leakage.

Note that, at each iteration \( i \), it is important to update the priorities according to the interference caused by the user selected in previous iterations, that is

\[
q_k^{(i)} = \left\| \Pi - \sum_{j=1}^{i-1} w^{(j)}_k (w^{(j)}_k)^H \right\| a_k \right\|^2,
\]

where \( w^{(j)}_k \) is the precoder obtained at the iteration \( j \) for the selected user \( k \). The iterative procedure continues incorporating these candidate users as selected users if the new candidate improves the secrecy sum-rate; otherwise, it is discarded and the iterative procedure ends.

As in the previous scenario, we provide a glimpse of the approached procedure in Alg. 1 since it follows the same lines as in the TC case. Nevertheless, the legitimate user priorities \( q_k \) and the precoder design have to incorporate the particularities of [7]. Contrary to TC, in the PC case each user has its own leakage subspace defined by \( \mathbb{L}_k = \text{span}(a_{v_1}, a_{v_2}, \ldots, a_{|E_k|}) \) and \( v_1, v_2, \ldots, v_{|E_k|} \in \mathbb{E}_k \). As a consequence, we only need to guarantee that the precoder for the user \( k \) lies in the subspace \( \mathbb{L}_k^\perp \) to force the condition \( \text{LINR}_{\text{PC}} = 0 \), thereby simplifying the objective function in (9). To that end, we define the orthogonal projector into the subspace \( \mathbb{L}_k^\perp \) as \( \Pi_k \) and set the initial priorities as \( q_k^{(0)} = \| \Pi_k a_k \| \), such that only the eavesdroppers in \( \mathbb{E}_k \) affect whether user \( k \) is scheduled or not. Then, the iterative procedure starts and the candidate user selection at the \( i \)-th iteration is performed using (10). Notice that the TC-ZF precoding design in (11) is not valid in this scenario, as the leakage subspace is not common to all the users. As such, for each \( k \in S^{(i)} \) we define the matrix

\[
B^{(i)}_k = [a_k, a_{j_1}, a_{j_2}, \ldots, a_{j_{i-1}}, a_{v_1}, a_{v_2}, \ldots, a_{v_{|E_k|}}]^T,
\]

where we included the channel vectors for user \( k \), for the \( i-1 \) users in \( S^{(i)} \) such that \( j_1, \ldots, j_{i-1} \neq k \), and the ones for the eavesdroppers \( v_1, v_2, \ldots, v_{|E_k|} \in \mathbb{E}_k \). Then, the PC-ZF precoder is computed as

\[
\omega_k = \left( B^{(i)}_k \right)^H B^{(i)}_k \left( B^{(i)}_k \right)^{-1},
\]

i.e., the first column of the former matrix computation. As such, we ensure that the precoder for each user \( k \in S^{(i)} \) belongs to the intersection of the subspaces \( (S^{(i),k})^\perp \cap \mathbb{L}_k^\perp \). Again, the precoders are normalized by \( w_k = \omega_k / \| \omega_k \| \), \( \forall k \in S^{(i)} \).
$S^{(i)}$ and waterfilling is used for power allocation $\mathbf{P}$. Regarding the update of the priorities in (12), the same expression can be used but now including the projector $\Pi_k$.

The key difference of this second scenario is that the legitimate user $k$ is only forced to deal with the LINR corresponding to those eavesdroppers clustered around him, which in turn are known to be the more detrimental ones for physical layer security [17]. Therefore, the available DoF for precoding are larger, in general, than in the TC scenario. This additional flexibility will be more effectively exploited in the case of the SW model, as it increases the advantages of the extra DoF provided by the distance.

### IV. Numerical Results

We now evaluate the performance of the joint secure precoding and scheduling LSP schemes, and investigate the impact of SW propagation in the XL-MIMO regime compared to the case of incorrectly assuming PW propagation. We consider a BS with $M = 100$ antennas equispaced $d = \lambda/2$, giving service to a set of randomly located users as follows: $K_B$ legitimate users are deployed randomly along the coverage region described in Table I at positions $\theta_k$ and $r_k$, then, a number of eavesdroppers $k_e$ is deployed in the vicinity of each legitimate user at positions $\theta_{e,k}$ and $r_{e,k}$ for $e = 1 \ldots k_e$, so that $K_E = K_B \cdot k_e$. Specifically, one eavesdropper is always located approximately in the same angular direction as user $k$ (i.e., $\theta_{1,k} = \theta_k + \Delta_k$, with $\Delta_k \sim \mathcal{U}(\pm 0.1^\circ)$), and $r_p$ meters closer to the BS. The remaining $e = 2 \ldots k_e$ eavesdroppers are deployed at a distance $r_q = r_{\text{Crit}}$ m from Bob (i.e., $r_q$ is the radius of a protected zone, on which no eavesdroppers are placed close to Bob) and a certain $\theta_{e,k}$.

The achievable secrecy sum-rate (Fig. 1) and the number of served legitimate users (Fig. 2) are shown for the case of the TC scenario, worst-case situation [8] where all the eavesdroppers cooperate to decode the legitimate messages, under the PW and SW propagation models. Solid and dashed lines denote the cases with $K_B = \{10, 20\}$ legitimate users, respectively, and the remaining set of parameters is listed in Table I with $r_p = 2r_q$ and $D = Md$. From the observation of Fig. 1 some remarks are in order: (i) under the PW model, the secrecy sum-rate is reduced due to the position of the eavesdroppers, and chiefly those located in similar angular directions as the legitimate users; (ii) the consideration of the SW model allows to improve the secure transmission rates and to serve more users, since legitimate users and eavesdroppers with similar angular directions are decorrelated with distance [8]; (iii) increasing the number of legitimate users notably improves the secrecy sum-rate in the SW case, which is not the case when considering PW; (iv) although the number of served users is not the metric being optimized, we see that in this setting LSP manages to improve both the secrecy sum-rate and the average number of served users when $K_B = 20$, compared to conventional ZF precoding [8]. Note that both ZF and LSP resort to waterfilling to determine the power allocation. As a consequence, the use of this method is directly related to the number of legitimate users being allocated power. Indeed, users receive power only if their effective channel gain, i.e., the gain obtained when the information leakage and the interference from the other legitimate users are removed, are over a certain threshold, say $\mu$. The value of $\mu$ increases with the number of users receiving power, and decreases with the SNR and the effective channel gains. Accordingly, since ZF approach gets, in general, more balanced effective gains as

### Table I: Simulation parameter settings.

| Parameter               | Value               |
|-------------------------|---------------------|
| Channel realizations    | 1000                |
| # legitimate users      | $K_B = \{10, 20\}$ |
| # eavesdroppers per Bob| $k_e = \{2TC, 6PC\}$ |
| Wavelength              | $\lambda = 0.1249$ m |
| Distance between antennas| $d = \frac{\lambda}{4}$ m |
| Number of antennas      | $M = 100$           |
| Transmit signal-to-noise ratio (SNR) | $[0, 5, 10, 15, 20, 25]$ dB |
| Rayleigh distance       | $r_{\text{Rayl}} = \frac{2D^2}{\lambda}$ m |
| Critical distance       | $r_{\text{Crit}} \approx 9D$ m |
| Distance range          | $[3r_{\text{Crit}}, r_{\text{Rayl}}]$ m |
| Angular range           | $[-\frac{\pi}{4}, \frac{\pi}{4}]$ rad |
users are not prioritized as in LSP, we can expect that the number of served users is larger when using ZF compared to LSP. This intuition can, however, fail when the SNR and/or the effective channel gains are not large enough, as we can see in Fig. 2. Thus, the increase on \( \mu \) due to the number of served legitimate users cannot be compensated due the poor effective channel gains obtained in this scenario.

The achievable secrecy sum-rate (Fig. 3) and the number of served legitimate users (Fig. 4) are shown for the case of the PC scenario, under the PW and SW propagation models. We increase \( k_e = 6 \) so that each legitimate user is affected by a larger number of potentially detrimental eavesdroppers compared to the TC case. These new eavesdroppers are deployed at a distance \( r_{e,k} \) from Bob with the angles \( \theta_{e,k} \) uniformly distributed. From the new two figures, Fig. 3 and Fig. 4, we extract several remarks: (i) under the PW model, the secrecy sum-rate is low because close-by eavesdroppers have a dominant effect; (ii) this is not the case when considering SW propagation, under which the secrecy sum-rate improves by taking advantage of the attenuation of leakage with distance; (iii) recall that ZF is forced to compute interference cancellation for all users, regardless whether they may not be allocated any power in the waterfilling procedure. As the information leakage is not as severe as in the TC case, the effective channel gains are larger that in the previous scenario. Therefore, LSP prioritizes users with large effective channel gains, whereas ZF distributes the power among legitimate users whose effective channel gains are more evenly distributed. Thus, LSP achieves better secrecy sum-rates despite serving fewer users, an effect directly related to the SNR that is better appreciated in high-SNR regimes.

V. CONCLUSION

We showed that considering SW propagation in an XL-MIMO system allows to significantly reduce information leakage to eavesdroppers in the same angular directions, compared to PW propagation. This new DoF allows SW to reach higher secrecy-sum rates and to serve more users than in the PW case, specially in the worst case scenario on which all eavesdroppers collude, and becomes more beneficial as we increase the number of users. We proposed a novel scheduling and precoding strategy that outperforms conventional zero-forcing strategies in terms of secrecy-sum rate.

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