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Robust Beamforming Optimization for Multi-Antenna Wireless Networks Under Channel Uncertainty

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Abstract
Movable Antennas (MAs) introduce an extra degree of freedom to space because they enable the mobility of the radiating antenna within a finite space. This feature may increase the gain of the instantaneous channel and thus enhance the reliability and spectrum efficiency of wireless communication channels. Nonetheless, this advantage relies On Channel State Information (CSI), which in turn is not independent of the position and is imprecise in practice. Current robust MAs have been studied by modeling the uncertainty in CSI through either fixed error or stochastic channel parameters. These kinds of models are helpful in analyzing the problem; nonetheless, they do not explicitly show the uncertainty in channel reconstruction.A simple robust beamforming scheme that incorporates a CSI uncertainty radius dependent on displacement from a reference point is proposed in this work.The model is physically motivated by channel reconstruction error, measurement uncertainty, and local spatial interpolation. For a two-antenna multiple-input single-output system, a closed-form worst-case received signal expression is derived using the norm-bounded uncertainty model. This leads to a simple robust design rule: antenna movement is beneficial only when the nominal channel-gain improvement exceeds the increase in uncertainty caused by displacement. The resulting position-selection problem reduces to a one-dimensional maximization of an effective robust channel margin. Numerical evaluation shows that the proposed criterion can select a position close to the calibration point rather than the position having the largest nominal channel gain. Monte Carlo simulations further show that this conservative movement strategy can eliminate outage in the considered example while requiring substantially less transmit power than a fixed reference-position design. The proposed model provides a low-complexity analytical tool for incorporating practical CSI-reconstruction limitations into MA position optimization.

Keywords: Movable antenna, Fluid antenna, Imperfect CSI, Robust beamforming, Channel uncertainty, Position optimization, 6G wireless communications.

1. Introduction

Future wireless networks are increasingly exploring antenna architectures that can adapt their spatial configuration to the propagation environment. MAs and fluid antenna systems (FAS) are particularly attractive because the radiating element is not restricted to a conventional fixed location. Instead, it can be mechanically or electronically reconfigured within a prescribed spatial region. This additional degree of freedom allows the communication system to search for favorable channel conditions without requiring many simultaneously active RF chains (Wong *et al.*, 2021; Zhu *et al.*, 2023a).The basic idea is straightforward. Because a wireless channel varies with position, moving an antenna by a fraction of a wavelength can substantially change the relative phase of multipath components. Consequently, choosing an appropriate position may lead to constructive interference, enhancing channel gain or minimizing interference. This is what some recent MA studies have shown in the cases of multiuser

transmissions, beamforming, spatial multiplexing, and sensing and communication (Zhu *et al.*, 2023b; Cheng *et al.*, 2024; Qin *et al.*, 2024; Wang *et al.*, 2024).

It is practically difficult because optimizing the antenna position requires perfect CSI in the movement area. Perfect CSI is not possible because there are several sources of error, including pilot noise, sampling density, channel estimation, hardware limitations, and unknown antenna position.This issue is particularly relevant for FAS and MA architectures because the channel must be estimated or reconstructed over a spatial region rather than at one permanently fixed antenna location. New *et al.* (2025), for example, showed that channel reconstruction accuracy depends strongly on the spatial sampling strategy and demonstrated that oversampling can be important for accurate FAS channel reconstruction.

Consequently, optimizing an MA using only nominal CSI can select a position whose apparent channel advantage disappears when the actual channel differs from the estimate. Robust optimization provides a natural solution. Recent work has already considered norm-bounded and random CSI errors for MA position optimization, including closed-form worst-case received-power expressions and graph-based position-search methods (Ma *et al.*, 2025). More recently, Chen and Sun (2026) considered joint robust beamforming and MA position optimization with stochastic errors in channel parameters.A fixed uncertainty radius assumes that the quality of CSI is approximately identical throughout the movement region. This is not always an assumption that is relevant in the case of CSI estimation based on spatially sampled measurements. This is because the farther away the antenna is from a known reference point, the more likely it is for there to be interpolation, extrapolation, and positioning errors.To capture the effects of mobility with a simple channel estimation model, this paper proposes a very simple idea of the uncertainty radius that is dependent on position. It has a measured baseline error added to a quantity proportional to the distance from a calibration point. This results in the natural robust channel margin, where the measured channel gain through the movement should be large enough to cover the extra uncertainty generated by the movement. Contributions of this work are listed below:

1. A CSI uncertainty model aware of the calibration procedure is presented, with the uncertainty radius depending on the antenna displacement.
2. A closed-form solution of the robust beamformer design is presented for a two-antenna MISO system by relying only on the norm of the channel estimate.
3. The condition of mobility gain is explicitly stated as a simple condition for checking the usefulness of the antenna movement when CSI is inaccurate.

The proposed technique is intentionally lightweight and does not involve semidefinite programming, stochastic optimization, nor iterated beamformer design.

2. Relation to Existing MA and FAS Research

There have been rapid developments regarding the idea of exploiting the motion of the spatial antenna recently. The FAS enables an antenna to switch between spatial ports, while, on the other hand, a MA a generic term for a radiating element whose location may be varied (Wong *et al.*, 2021; Zhu *et al.*, 2023a).Both architectures exploit the spatial variation of the electromagnetic field.Several studies have established the channel and optimization foundations of these systems. Zhu *et al.* (2023b) developed a field-response-based MA channel model and analyzed the associated performance. Zhu *et al.* (2023c) investigated multiuser communication with MA position optimization and demonstrated that antenna placement can be jointly exploited with conventional beamforming. Cheng *et al.* (2024) studied sum-rate maximization for fluid-antenna-enabled multiuser communication, while Qin *et al.* (2024) considered joint antenna positioning and beamforming.

Efficient position-search methods have also been investigated. Mei *et al.* (2024) formulated MA position selection using a graph-based representation, converting spatial selection into a discrete optimization problem. Learning-based approaches have subsequently been considered for more complicated multiuser and ISAC scenarios (Wang *et al.*, 2024; Waqar *et al.*, 2024).CSI acquisition is an equally important part of the problem. New *et al.* (2025) showed that reconstructing the spatial channel in FAS can require more careful sampling than a simple half-wavelength rule would suggest. This observation motivates treating CSI uncertainty as a spatially varying quantity rather than automatically assigning the same error radius to every antenna position.

Robust MA optimization has now become an active research direction. Ma *et al.* (2025) considered norm-bounded and random CSI errors and derived robust position-selection solutions for MISO MA systems. Chen and Sun (2026) further considered joint robust beamforming and position optimization with stochastic uncertainty in angular and path-gain parameters.The distinction of the present work is therefore the form of the uncertainty model and its analyticalinterpretation. Rather than introducing a new general-purpose robust optimiser, the proposed method links the uncertainty radius directly to the displacement from a calibrated position. This produces an interpretable tradeoff between spatial channel improvement and loss of CSI confidence.

3. Physical Motivation and System Model

Consider a single-user downlink with two transmit antennas. One antenna is fixed, while the second is movable along a one-dimensional rail. The MA position is denoted by x, with $x \in [-, DD]$. A reference position $x_0$is selected during channel calibration.For a multipath environment, moving the antenna changes the relative phase of the propagation paths. A representative far-field channel for the movable element can be written as a sum of path contributions in Eq. (1)

$$h_2(x) = \sum_{\ell=1}^{L} a_\ell \, e^{j\phi_\ell} e^{-j(2\pi/\lambda)x \sin\theta_\ell}. \qquad (1)$$

Eq. (1) is not intended to represent every MA propagation environment. Rather, it provides a transparent physical explanation of why small antenna movements can produce substantial channel variations. Similar field-response descriptions have been used in MA channel modeling (Zhu *et al.*, 2023b).Let $\widehat{\boldsymbol{h}}(x)$denote the estimated two-element channel. The actual channel is modeled as in Eq. (2)

$$\boldsymbol{h}(x) = \widehat{\boldsymbol{h}}(x) + \boldsymbol{e}(x), \qquad (2)$$

where $\boldsymbol{e}(x)$represents the aggregate CSI error.The important observation is that the error need not be spatially constant. Suppose the channel error at the calibration point satisfies $\| \boldsymbol{e}(x_0) \| \leq \epsilon_0$. If the local reconstruction error changes smoothly with position, a conservative Lipschitz-type bound can be written as in Eq. (3)

$$\| \boldsymbol{e}(x) \| \leq \epsilon(x) = \epsilon_0 + \alpha \, | \, x - x_0 \, |. \qquad (3)$$

Here, $\epsilon_0$represents the baseline error at the calibration position, while αdescribes how rapidly the uncertainty grows with displacement.This model has a practical interpretation. The baseline term can incorporate pilot noise and local channel-estimation error. The slope αcan capture spatial interpolation error, imperfect channel reconstruction, position uncertainty and other effects that become increasingly relevant away from the calibration point. It is therefore preferable to interpret αas an experimentally estimated uncertainty sensitivity, rather than as a universal propagation constant. Figure 1 shows the conceptual system configuration showing the fixed antenna.

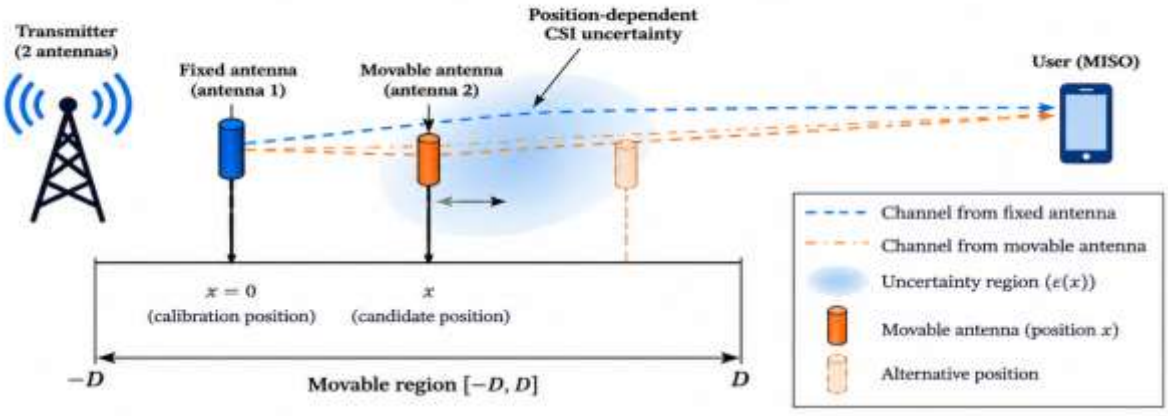


Figure 1. Conceptual system configuration showing the fixed antenna, MA, calibration position x_0, candidate position x and position-dependent CSI uncertainty.

4. Robust Beamforming Formulation

Denote the transmit beamforming vector by w and the target received SNR by γ_0. This problem is to find the antenna configuration and beamformer that minimises the transmit power under the constraint that the target SNR holds for all channel errors within the prescribed uncertainty set.The robust design can be summarized as in Eq. (4)

$$\min_{\boldsymbol{w},x} \| \boldsymbol{w} \|^2 \ \text{ s.t.} \min_{\|\boldsymbol{e}(x)\| \leq \epsilon(x)} \frac{| \left(\widehat{\boldsymbol{h}}(x) + \boldsymbol{e}(x) \right)^H \boldsymbol{w} |^2}{\sigma^2} \geq \gamma_0. \qquad (4)$$

For a fixed antenna and beamformer, the worst-case error is in the direction that results in nullification of the received signal. The triangle inequality and the Cauchy-Schwarz inequality led to the worst-case effective channel magnitude as in Eq. (5)

$$\min_{\|\boldsymbol{e}\| \le \epsilon} \left| \left(\widehat{\boldsymbol{h}} + \boldsymbol{e}\right)^H \boldsymbol{w} \right| = \left[\left| \widehat{\boldsymbol{h}}^H \boldsymbol{w} \right| - \epsilon \, \| \boldsymbol{w} \| \right]_+. \qquad (5)$$

This equality is physically intuitive since the most harmful CSI error is in the exact opposite direction of the beamformed channel.For a fixed position, maximum-ratio transmission remains optimal because it maximizes the nominal projection of the channel onto the beamformer. Consequently, the robust transmit power required at position $x$becomes

$$P_{\mathrm{R}}(x) = \frac{\gamma_0 \sigma^2}{\left(\| \widehat{\boldsymbol{h}}(x) \| - \epsilon(x) \right)^2}, \quad \| \widehat{\boldsymbol{h}}(x) \| > \epsilon(x) \qquad (6)$$

Eq. (6) provides the central result of the proposed framework. Antenna movement does not need to maximize the nominal channel norm alone. Instead, it should maximize the robust channel margin

$$M(x) = \| \widehat{\boldsymbol{h}}(x) \| - \epsilon(x). \qquad (7)$$

Eq. (7) shows the optimum position is consequently the point that maximizes $M(x)$. This converts the robust beamforming problem into a one-dimensional position search followed by conventional maximum-ratio transmission.

5. Mobility-Benefit Interpretation

The proposed formulation leads to a simple engineering interpretation.Let $H(x) = \| \widehat{\boldsymbol{h}}(x) \|$denote the nominal channel norm. Relative to the calibration position, movement to $x$provides a nominal channel improvement of $H(x) - H(x_0)$. At the same time, the uncertainty model introduces an additional penalty proportional to $| x - x_0 |$.

Therefore, movement is useful only when the channel improvement is sufficiently large to compensate for the uncertainty penalty. For $\alpha > 0$, this condition can be expressed through the threshold in Eq. (8)

$$\alpha_{\mathrm{th}}(x) = \frac{H(x) - H(x_0)}{| x - x_0 |} \qquad (8)$$

A movement is attractive under the proposed robust model when its uncertainty slope is below the improvement rate represented by $\alpha_{\mathrm{th}}(x)$.This result is useful because it provides a physical interpretation that is absent when a constant uncertainty radius is assumed. A position with a very high nominal gain may nevertheless be undesirable if reaching it requires a large displacement from the region where CSI is reliable.

The proposed position-dependent uncertainty model can be interpreted as a reliability-aware extension of conventional robust MA design. In a fixed-radius formulation, every candidate position is treated as if the same level of CSI confidence were available throughout the movement region. The present formulation separates two effects that are otherwise combined into a single constant parameter. The first is the baseline uncertainty that exists even at the calibration point. The second is the incremental loss of confidence associated with displacement from that point. This separation is important because an antenna position can have a favorable nominal channel while still being poorly characterized. The proposed model therefore does not reject antenna mobility; rather, it makes the reliability of the available CSI an explicit part of the position-selection process.

The physical interpretation is also consistent with the spatial nature of channel acquisition in MA and FAS systems. Channel information must be acquired or reconstructed across a region where the radiating element might operate, rather than at one fixed point. New *et al.* (2025) demonstrated that the channel reconstruction is affected by the spatial sampling scheme employed and that oversampling might be needed for improving the accuracy of reconstruction. This gives a good rationale for considering uncertainty as something dependent on location. In our framework, this is modeled by an empirical way in the form of the baseline plus displacement model. The idea is not to replicate the whole process of sampling, interpolation, and reconstruction but to capture their combined effect via an empirically determined uncertainty envelope.

It is also appropriate to consider the uncertainty region as the set providing the confidence of the optimization process at any candidate position for an antenna. The set is determined from the measurement of the baseline error at the calibration point. As the antenna gets away from that point, the radius increases following the uncertainty sensitivity. A bigger radius shows that more channel realizations have to be considered to ensure the desired SNR. This explains the compatibility of the framework with current MA channel models. The nominal channel could be obtained from the field response or multipath model, but the uncertainty model will be applied to the error between

the nominal and actual channel. In other words, the two models are different in their purpose. The former is used to describe the spatial variation, while the latter describes the confidence in this variation.

For the two-antenna MISO configuration, the robust design has an additional structural advantage. Once the position is fixed, the uncertain channel enters the received signal through a scalar beamformed projection. The worst-case error is therefore the realization that most strongly opposes the nominal projection. The resulting lower bound on the effective channel magnitude depends on the nominal channel magnitude and the uncertainty radius, rather than on the full orientation of the channel vector. This is why the original nested robust problem can be reduced to a simple expression involving the channel norm and the position-dependent uncertainty term. The reduction is particularly useful for the proposed study because it isolates the effect of calibration-aware uncertainty from other optimization complications.

Maximum-ratio transmission retains its role as the fixed-position solution because the objective is to maximize the useful nominal projection for the single-user receiver while accounting for a norm-bounded perturbation. The uncertainty penalty is consequently introduced after the nominal beamforming direction has been identified. This separation means that the proposed method does not require an iterative alternation between antenna movement and beamformer design. Instead, candidate positions are evaluated through their robust channel margins, and the beamformer is then aligned with the estimated channel at the selected position. The resulting sequence is simple enough to support rapid position evaluation while preserving the worst-case interpretation of the uncertainty model used in the formulation.

The suggested framework will also help to understand the concept of performance comparison. A nominal solution represents the position selected solely from the estimated channel. A fixed-radius robust solution represents a design that assumes a common uncertainty level across the movement region. The proposed solution instead evaluates each position using the uncertainty associated with that position. These strategies can therefore choose different operating points even when they use the same nominal channel model and the same beamforming architecture. The numerical comparison in this paper is designed around that distinction. Its purpose is not to establish that movement is always advantageous or that calibration proximity is always preferable, but to demonstrate that the decision depends on the balance between spatial channel gain and spatial CSI confidence.

Finally, the proposed formulation is intentionally conservative. The linear uncertainty law is an upper-bound approximation and does not imply that every realization of estimation error grows linearly with displacement. Likewise, the worst-case beamforming result does not claim that the actual channel will continuously attain the most adverse point in the uncertainty region. The value of the formulation lies in converting uncertain spatial reconstruction into an explicit design margin. When the uncertainty set is appropriately calibrated, the margin gives the optimizer a transparent way to distinguish nominal improvement from improvement that can be supported with the available CSI confidence. This provides the analytical basis for the numerical and Monte Carlo investigations that follow, while preserving the original scope of a two-antenna, single-user MISO system.

6. Numerical Evaluation

A representative two-path environment is considered to illustrate the proposed method and its simulation parameters are given in Table 1. The carrier wavelength is set to 0.1m and the movable region is $[-, 0.250.25]$m. The calibration position is $x_0 = 0$. The two path amplitudes are 1 and 0.75, with departure angles of $20°$and $-35°$, respectively. The corresponding path phases are 0.2 and 1.1 rad.The baseline uncertainty is set to $\epsilon_0 = 0.08$, while the uncertainty sensitivity is $\alpha = 0.55\ \mathrm{m}^{-1}$. A target SNR of 10 dB is used with normalized noise power $\sigma^2 = 1$. The antenna position is evaluated over a 1001-point spatial grid.

Table 1. Simulation parameters

Parameter	**Value**
Wavelength	0.1 m
Movable region	$[-, 0.250.25]$m
Calibration position	0 m
Path amplitudes	1, 0.75
Path angles	$20°, -35°$
Path phases	0.2, 1.1 rad
Baseline CSI error	0.08

Uncertainty slope	$0.55\ \mathrm{m}^{-1}$
Target SNR	10 dB
Noise power	1
Position samples	1001

The nominal channel norm reaches its maximum at approximately $x = 0.0935\text{m}$, where $H(x) \approx 2.3574$. However, this position is displaced from the calibration point, giving an uncertainty radius of approximately 0.1314. The proposed robust criterion instead selects approximately $x = -0.015\text{m}$. At this location, the nominal channel norm is almost identical, approximately 2.3572, but the uncertainty radius falls to approximately 0.0883.

Table 2. Position-selection comparison

Strategy	**Position (m)**	**Channel norm**	**Actual uncertainty**	**Required power**
Nominal CSI	0.0935	2.3574	0.1314	1.7994
Constant-radius robust*	0.0935	2.3574	0.1314	1.9280
Proposed	-0.0150	2.3572	0.0883	1.9425
Fixed reference	0	2.2338	0.0800	2.1557

As Table 2 depicts, the constant radius method makes use of the radius 0.08 that has been assumed.However, since the position-dependent radius of 0.0935 m has a larger uncertainty value, the constant radius solution cannot be regarded as a robust solution according to the proposed uncertainty framework. As for the proposed scheme, it needs more power compared to the nominal method since it accounts for the CSI uncertainty. However, it results in the power being reduced compared to staying at the calibration point.

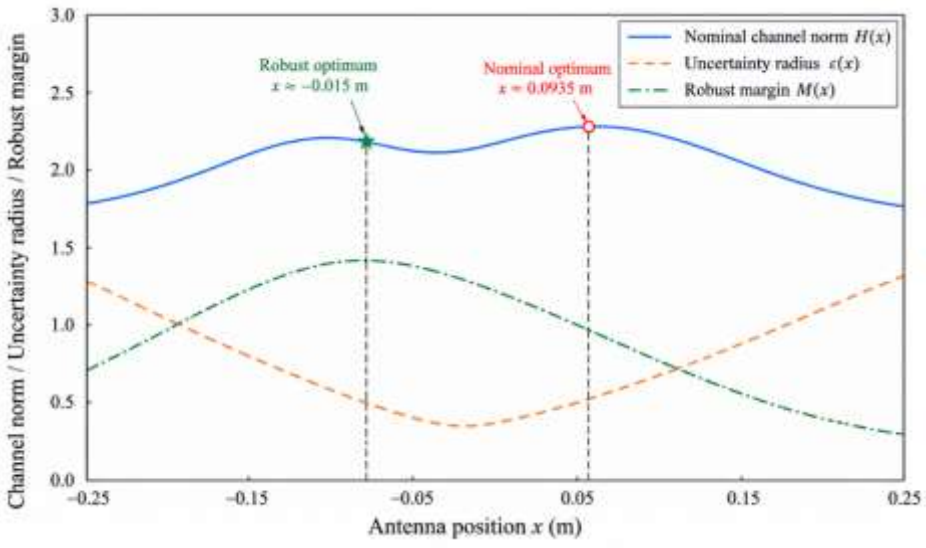


Figure 2. Nominal channel norm $H(x)$, uncertainty radius $\epsilon(x)$, and robust margin $M(x) = H(x) - \epsilon(x)$.

Her in Figure 2, the nominal channel margin is optimized at a location that is away from the calibration location, while robust margin is optimized near the calibration location.

7. Monte Carlo Robustness Verification

To verify the analytical worst-case model, 200,000 random CSI-error vectors were generated within the prescribed uncertainty ball for each evaluated strategy. The target SNR was 10 dB.Three transmission strategies were compared. The first uses the nominal channel and does not explicitly account for CSI uncertainty. The second applies a constant uncertainty radius of 0.08. The third uses the proposed position-dependent uncertainty model.The nominal strategy produced an outage probability of approximately 49.5% under the simulated actual errors. This large outage is expected because the selected position maximizes nominal channel gain without protecting against channel mismatch.The constant-radius robust strategy reduced the observed outage to

approximately 4.7%. However, this result should be interpreted carefully: the actual uncertainty at its selected position exceeds the assumed constant radius. Therefore, its reduced outage does not constitute a worst-case guarantee.The proposed strategy produced zero observed outages in the 200,000-trial experiment. The average spectral efficiencies were approximately 3.46-, 3.55-and 3.56-bit/s/Hz for the nominal, constant-radiusand proposed schemes, respectively.

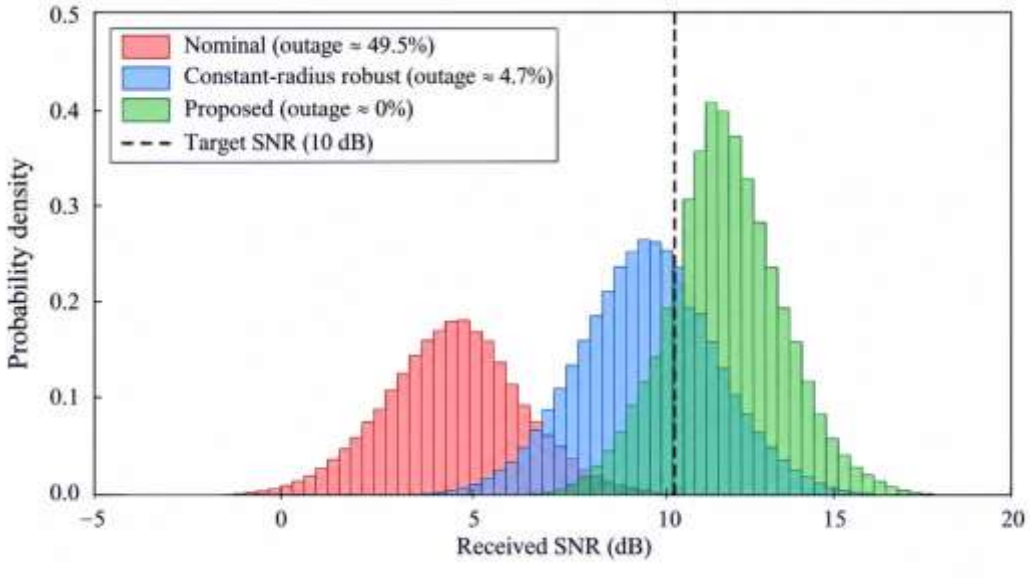


Figure 3. Empirical received-SNR distribution from 200,000 random CSI-error realizations.

The proposed strategy maintains the target SNR under the simulated uncertainty region, consistent with the analytical worst-case design as seen from Figure 3.The simulation should not be interpreted as proof of a universal zero-outage property. The analytical guarantee applies only when the actual CSI error is contained within the specified uncertainty set. The Monte Carlo experiment instead verifies that the closed-form bound behaves as expected for the chosen channel and error model.

8. Sensitivity to the Uncertainty Slope

The uncertainty sensitivity αdetermines how strongly antenna movement is penalized. When $\alpha = 0$, the model reduces to a constant uncertainty radius and the optimizer favors the nominal high-gain position. As αincreases, the optimizer moves progressively closer to the calibration point.For the considered channel, the selected position changes from approximately 0.0935 m at $\alpha = 0$to approximately -0.014m when αreaches 1.5 m^{-1}. The corresponding robust transmit power increases gradually from approximately 1.928 to 1.967.A larger value of αindicates that confidence in reconstructed CSI deteriorates more rapidly with movement. The optimizer therefore becomes increasingly conservative.The result also demonstrates why αshould preferably be obtained from measurements. If the uncertainty grows slowly across the movement region, larger antenna movements can be exploited safely. If reconstruction deteriorates rapidly with distance from the calibration point, the optimal operating point should remain closer to the calibrated region.

9. Practical Implementation Considerations

The proposed model can be implemented without modifying the underlying antenna hardware, requiring only an initial calibration procedure to estimate the spatial uncertainty envelope by collecting reference channel measurements at known antenna positions and comparing them with reconstructed or predicted CSI. During optimization, the estimated channel norm and corresponding position-dependent uncertainty radius are evaluated for each candidate position and the position that maximizes the robust margin is selected before applying conventional maximum-ratio transmission. This lightweight structure avoids solving a large joint nonlinear optimization problem, with the computational burden mainly determined by channel evaluation across candidate positions. The framework can further accommodate nonlinear uncertainty growth when supported by measurements, extend to two-dimensional antenna surfaces using directional uncertainty sensitivities and incorporate antenna movement energy or reconfiguration cost when these factors become significant.

10. Limitations

Limitations that need to be considered include the following: First, the numerical analysis assumes a single-user scenario for two antennas. It is deliberately simple, but not meant to serve as a general solution for multiuser MA

systems. Second, the uncertainty model is a local model. The linear relationship with displacement is justified as a first-order conservative model, but needs experimental validation before use as an overall reliability model for the system. Third, the propagation model assumes a far-field multipath environment. Near-field conditions, wideband channels, mutual coupling, and radiation patterns specific to the hardware can affect position-dependent characteristics in addition to those included in the model. Fourth, there is no explicit account of time taken/energy used to relocate the antenna in the study. In any real system design, the gain of relocation must be balanced against delay and switching overhead. The above limitations have very clear directions for future research. Measured values of MA/FAS channel data can be used to determine the spatial uncertainty envelopes, whereas extensions for multiple users could explore the interaction of CSI uncertainty with inter-user interference.

11. Conclusion

In this work, we formulated a robust beamforming algorithm for mobile antennas in the presence of CSI errors, where the CSI uncertainty radius does not necessarily remain constant but increases as the antenna moves away from the reference point at which it was initially calibrated.For a MISO communication system with two antennas, we derived an analytical solution for the proposed robust optimisation problem. The maximum ratio transmission (MRT) scheme becomes the optimal one for any fixed location of the antenna, whereas the optimal location of the antenna is found by maximising the difference between the nominal channel norm and the position-dependent uncertainty.This trade-off can be observed from the numerical results. The position at which the nominal channel gain is maximized does not have to be the one with the best robust performance. By considering the variation of the CSI reliability with space, the new method chooses the position nearer to the calibration point while ensuring the target SNR.This contribution is deliberately modest and clear from an analytical perspective. This contribution neither substitutes nor supplements the state-of-the-art robust MA optimization algorithms; rather, it supplies a physical uncertainty model and a simple design guideline that can be used as a baseline or incorporated into more complex algorithms for MA, FAS, near field and multiuser optimizations.

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