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An Efficient Method of Electromagnetic Transmitters Localization in Multipath Environment*

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Abstract

This paper explores the efficiency of the MUSIC algorithm in the domain of electromagnetic wave propagation in urban environment. The Multiple Signal Classification (MUSIC) algorithm, widely used in direction-of-arrival estimation, is examined for its ability to address the challenges posed by multipath propagation in urban environment. The study investigates the algorithm's robustness in the estimation of angles of electromagnetic wave arrivals in the complex, urban landscapes, considering factors such as reflections, diffractions, and signal interactions with various obstacles. The article presents the theoretical foundations of the MUSIC algorithm, explaining its principles and adaptive capabilities. Practical applications of the algorithm are explored within the context of electromagnetic wave propagation in urban area, indicating its potential for localization in complex, multipath environments. Using simulations, the study provides insights into the algorithm's performance under diverse conditions. The findings contribute to the understanding of MUSIC's applicability in urban environments, offering valuable implications for the localization of electromagnetic sources in challenging propagation scenarios. The main effort of the research is devoted to prove the authors hypothesis that MUSIC algorithm can not only show directions to many emitters but also find many paths that signal used to reach the receiver and this way obtain the actual localization of the transmitter by combining estimated azimuths for each signal path and the area structure. The presented research is an initial step for further exploration of advanced localization techniques in dynamic urban areas.

Keywords: multipath propagation, MUSIC algorithm, urban environments, localization

Introduction

Localization

In contemporary times, localization systems are playing a crucial role in many various fields [N. Tayem, A. Bochem, Y. Mao] such as autonomous navigation, robotics, augmented reality, logistics, emergency response and military operations [A Duarte], enabling precise positioning and context-aware services in both indoor and outdoor environments. Additionally, large number of users and systems causes a lot of different types of interferences, that could be harmful for other users, and localization of their sources is critical for proper operation of the system.

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Modern methods of localization are mostly based on triangulation, which involves a few devices placed in different locations and are able to estimate the DOA (Direction of Arrival) of incoming electromagnetic waves. Combining the DOAs from all devices and their locations makes is possible to determine the localization of the source of the emission.

Such methods can be used in the open areas where DOAs of upcoming signals indicates the direction to the emission source, provided that it is not moving while we base on a single measurement and not their series determining the direction of its move. The situation becomes more complicated when we take into consideration the environment with multipath propagation that causes more challenging problems [K. -H. Lam, V. Pudlovskiy, M. Feng].

Challenges of the urban environment

The most optimal conditions for wireless communications systems exist in the open area, where most of the localization methods are suitable. Unfortunately, modern systems are most often deployed in urban environments, where because of multipath propagation, the measured DOA is not necessarily the direction to the emitting device due to possible signal reflections between the emission source and direction-finding device.

Some MIMO (Multiple In, Multiple Out) solutions address this issue, however all of them require cooperation between both the transmitter and receiver, which is problematic in the situation where opponents are unwilling to assist each other.

These challenges serve as the starting point for this study, aiming to utilize signal multipath propagation to improve the accuracy of electromagnetic emitter localization in urban environments.

Backward Raytracing (BR)

The authors of this paper propose performing BR on estimated DOAs, which basically means to replicate the paths of the signal and find the transmitter site based on their intersection points. Such a scenario requires using a precise, 3-dimensional map of the area and the complex urban environment. Additionally, knowledge of materials used to create objects would be needed to estimate the number of reflections based on the pathloss parameter for each signal path.

This solution has only one crucial problem—how to detect a few signal paths while all triangular methods are dedicated to finding only one—the strongest path.

MUSIC Algorithm

The mentioned problem leads directly to the MUSIC algorithm [M Hawa] that seems to be very useful in this context [Q Liu, J. Zhang, S. P. Drake]. This is the algorithm that enables locating many emission sources working on the same frequency at the same time. Thus, it was assumed that from the point of view of the MUSIC algorithm, there is no difference between signals coming from different sources and the same signal coming from the same transmitter but from different directions.

The MUSIC algorithm exploits the structure of the received signal's covariance matrix [He Weigang, Z. -H. Liu, N. A. Lafta]. First, it collects the signal data from an array of sensors (e.g., antennas) and constructs a spatial correlation (covariance) matrix from the received signals. Then, this matrix is decomposed using eigenvalue decomposition into two orthogonal subspaces: the signal subspace and the noise subspace.

The key insight of the MUSIC algorithm lies in the fact that the noise subspace is orthogonal to the steering vectors corresponding to the directions of arrival (DoA) of the incoming signals. By scanning over all possible angles and projecting the corresponding steering vectors onto the noise subspace, the algorithm computes a so-called spatial spectrum, where peaks in this spectrum indicate the directions from which the signals are arriving.

As a result, the MUSIC algorithm can accurately estimate the direction of multiple incoming signals, even if they operate at the same frequency, provided they are spatially separable and the number of sources is less than the number of sensors.

The classical MUSIC algorithm has good performance for uncorrelated signals, but for correlated signals coming from the same source of signal but propagated using different paths, the results are often unsatisfying. That is why in the literature one can find modified algorithms dedicated to DOA of correlated signals [M. M. Gunjal].

Research Objective

In urbanized conditions, where electromagnetic emissions propagate to the receiver through multiple paths, precise source localization becomes challenging. The primary research objective is to explore the effective utilization of backward tracking of reflected electromagnetic signal paths to achieve accurate emitter localization in diverse urban terrains. During the research, a crucial problem emerged concerning the precise determination of DOA of reflected signals. How to efficiently do it?

The subsequent sections of the article are devoted to the methodology, enabling estimation of the DOA azimuths of reflected signals in urban conditions to utilize the backward tracking technique. The obtained results and conclusions drawn from the conducted research are also presented.

Methodology

Urban Environment Characterization

The study started with definition of the urban environment, where simulation studies were conducted using the MATLAB environment. The simulation model included a transmitter (TX) and receiver (RX) placed at the same heights, limiting measurements to the azimuth plane. Additionally, one building acted as a line-of-sight (LOS) obstacle, and two others were placed perpendicular to this obstacle, simulating urban structures from which the signal could reflect.

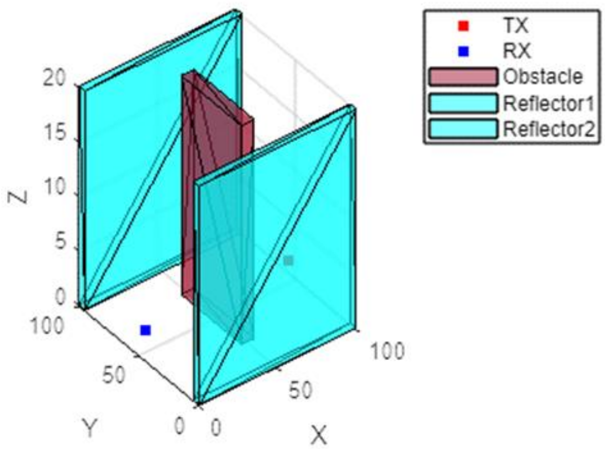

Fig. 1 Modelled terrain

Figure 1 illustrates the simulated urban scenario described above, highlighting the placement of the transmitter and receiver, as well as the surrounding buildings that influence signal propagation. The layout emphasizes the presence of the primary LOS obstacle and the reflective surfaces introduced by the perpendicular structures, providing a realistic representation of typical urban signal behavior.

Raytracing Utilization

To determine the signal trajectory, the raytracing function was applied, allowing precise identification of the angles at which the signal reached the receiver after reflections from buildings.

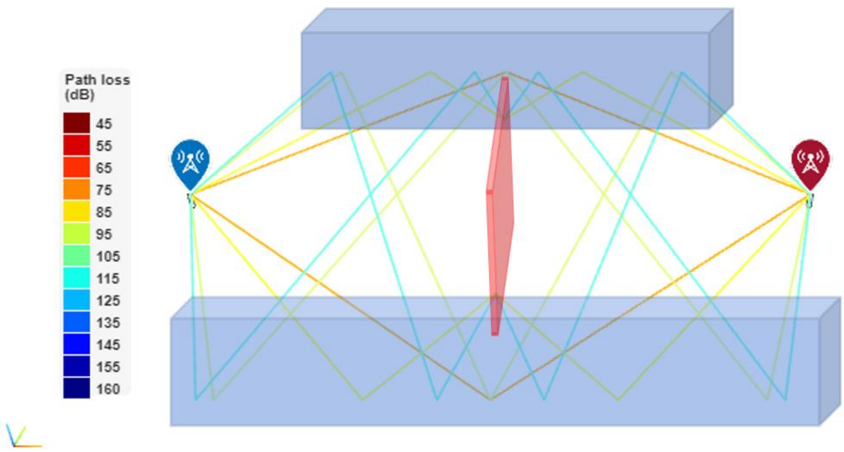

Fig. 2 Multipath propagation signal paths

Figure 2 visualizes the multipath propagation scenario generated using the ray tracing method, presenting various signal trajectories resulting from reflections off surrounding structures. The diagram shows how the signal reaches the receiver through the reflected paths, illustrating the complexity of urban signal behavior and the significance of angle estimation in such environments.

Estimation of DOA of reflected signals

For estimating DOA of reflected signals, a linear antenna array consisting of 20 isotropic elements was used. This configuration was chosen due to its capacity to capture spatial information with sufficient resolution while maintaining practical feasibility for field deployment. Given the necessity to resolve multiple, simultaneously incoming signals, the MUSIC algorithm was selected as the core method.

To evaluate the algorithm's performance under conditions reflecting realistic urban scenarios, characterized by limited data availability and various noise levels, a series of simulations was conducted. The Signal-to-Noise Ratio (SNR) was systematically changed from 1 dB to 50 dB, covering a wide range of propagation conditions. For each SNR level, 100 independent trials were performed to ensure statistically meaningful results. Importantly, each MUSIC estimation was based on a single snapshot of the received signal, which simulate situations where continuous tracking or long observation windows are not feasible, such as during short signal interception.

This evaluation framework enabled a comprehensive assessment of the MUSIC algorithm's robustness, sensitivity to noise, and overall reliability when applied to the problem of identifying the DOAs of reflected electromagnetic waves. These insights are essential for determining whether backward raytracing based on such estimations can be successfully applied in realistic urban localization tasks.

DOA determination

The obtained results were analyzed using circular histograms, each based on 100 independent samples. These histograms were used to visualize the distribution and frequency of detected DOAs across the full 360-degree azimuth plane. This approach allowed for a clearer understanding of the distribution of estimated DOAs across multiple simulation runs. To enhance interpretability and focus on the most significant directions, the resulting histograms were subsequently sorted in descending order with respect to the number of DOA detections corresponding to each angular sector (showing how many times signal was detected in each direction).

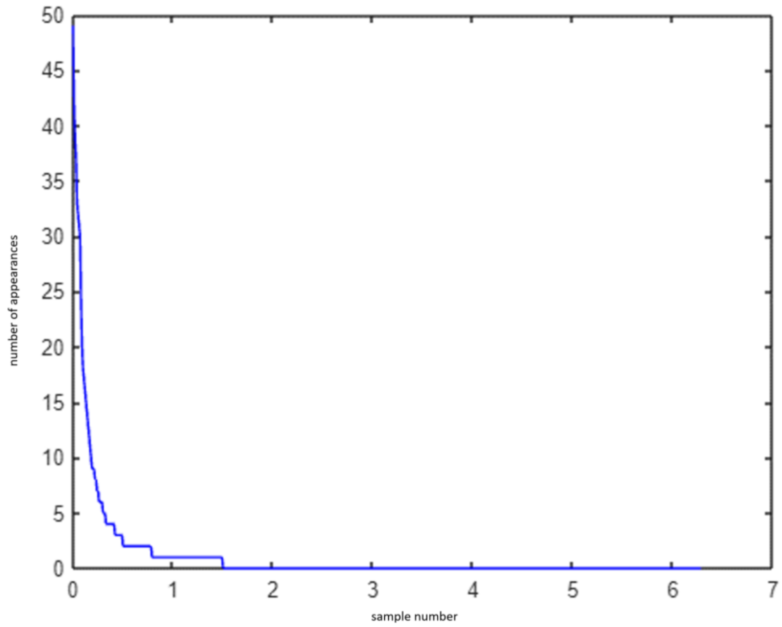

Fig. 3 Sorted histogram of numbers of detection in angle function

Figure 3 illustrates one of the sorted histograms, where angular sectors are ordered from the most to the least frequently detected DOA estimates. This visualization helps to highlight the dominant directions of arrival and to identify noise-related or spurious detections that occurred only sporadically.

Based on the analysis of such histograms, a quantitative threshold criterion was introduced and set as at least 10 appearances. This threshold was used to filter out unreliable DOA estimates—specifically, if the number of detections at a given angle fell below the defined threshold, those values were considered statistically insignificant and thus discarded. Among the remaining, more frequent detections, the angle with the highest occurrence was selected as the final, determined DOA for that simulation case.

This method ensured that the final DOA estimation was based not merely on isolated or random detections but rather on the statistically dominant signal direction—enhancing the robustness and reliability of the approach in conditions reflecting real-world multipath propagation and noise interference.

Utilization of DOA for BR

The determined DOA values, obtained through the MUSIC algorithm and refined using statistical thresholding, were subsequently employed as the basis for backward tracking of the signal paths.

To implement backward raytracing, each estimated DOA was projected in reverse from the receiver's location, simulating the potential trajectory that the signal could have followed before reaching the antenna array. The reverse paths were traced across the modelled terrain map, which accurately represented the physical layout of the environment, including buildings and other reflective surfaces. The propagation environment was treated as a three-dimensional space, though the analysis itself remained constrained to the azimuth plane, consistent with the simulation setup.

During this process, special consideration was given to the interactions between the signal paths and terrain obstacles. If a projected DOA line intersected with a known structure, a reflection point was assumed, and the signal trajectory was extended accordingly—simulating how the wave might have reflected off that surface on route from the emitter to the receiver. By iteratively applying this method for each significant DOA, multiple possible signal paths were reconstructed, allowing the estimation of potential source locations based on the intersections of these backward-propagated rays.

This approach enabled the exploration of emitter localization even in scenarios where the direct line-of-sight was blocked, relying instead on secondary and tertiary reflections that traditionally reduce the accuracy of localization.

Results

Results for a single sample

We initiated the analysis of the results by examining a single representative sample, with the goal of evaluating how effectively the MUSIC algorithm identifies the directions of arrival (DOA) of reflected signals under realistic conditions. This single snapshot analysis served as an initial benchmark, providing insight into the algorithm's capabilities and limitations when only short signal is available.

However, it quickly became evident that relying on a single measurement is not always sufficient for obtaining reliable and unambiguous DOA estimations. In such isolated cases, the results tend to exhibit greater variability, with a higher likelihood of detecting spurious angles caused by noise, signal correlation, or limited spatial resolution of the sensor array. Consequently, the precision of localization based on a single snapshot can be inconsistent, especially in multipath-dominated environments where multiple reflected signals arrive with similar strengths and delays. To visualize this effect, a graph was generated for the selected sample.

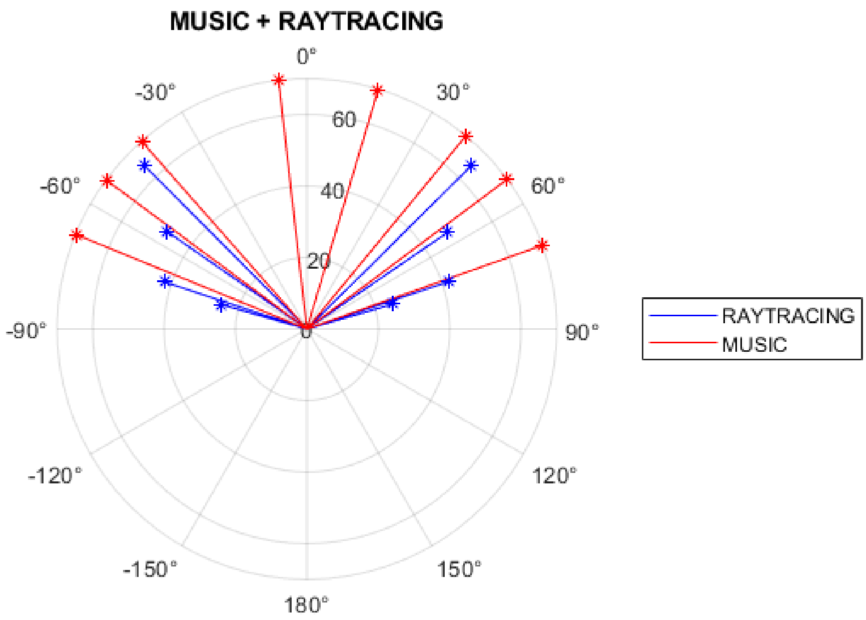

Fig. 4 Validation MUSIC results from 1 sample with raytracing data

In this plot, the blue lines represent the true azimuthal directions and relative levels of the specific rays arriving at the receiver—derived from the raytracing simulation. These lines serve as a ground truth reference for evaluating MUSIC’s output. In contrast, the red lines indicate the azimuths as detected by the MUSIC algorithm during the same snapshot. This side-by-side visualization provides a clear comparison between expected and estimated directions, revealing both the strengths and shortcomings of MUSIC when used with limited data.

Such analysis not only highlights the potential of the algorithm but also emphasizes the value of statistical aggregation over multiple snapshots, as explored in subsequent parts of the study.

Histograms of determined DOAs

Here are two obtained histograms before the cleaning process. It is based on the elimination of 'noisy' results and outliers. This process was necessary, as the data contained interferences and errors that could affect result accuracy.

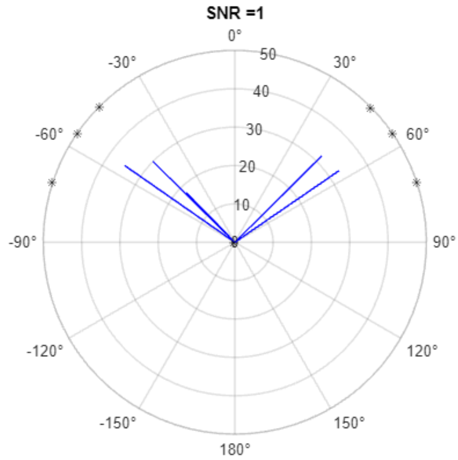

Fig. 5 Histogram obtained for SNR = 1 dB

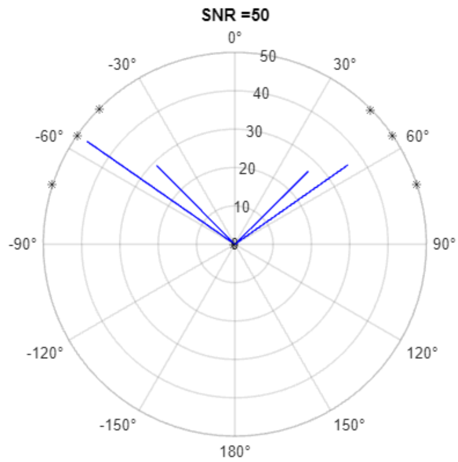

Fig. 6 Histogram obtained for SNR = 50 dB

The histograms presented above demonstrate, that within the examined range, the Signal-to-Noise Ratio (SNR) does not exert a significant influence on the overall performance of the MUSIC algorithm in this application. Both low and high SNR scenarios provide comparable results in terms of the number and position of dominant DOA peaks. Notably, the locations of the main maxima remain consistent across different noise levels, and the algorithm maintains a high level of accuracy in identifying the true signal directions. This consistency suggests that MUSIC exhibits a strong resilience to noise in the context of multipath signal analysis, making it a reliable method for direction estimation even under challenging conditions.

As a result of this cleaning process, each histogram was carefully and systematically analyzed to filter out erroneous or statistically insignificant samples while retaining the most essential and consistent information about the incoming signals. Although this procedure inevitably led to the loss of some data, particularly those signal components that occurred less frequently and may have represented weaker or more complex reflections, it was a necessary trade-off. These infrequent detections, while potentially meaningful, were more likely to introduce uncertainty or noise into the localization process. Therefore, their removal was crucial for improving the clarity, precision, and overall reliability of the final DOA estimations used in subsequent analysis steps.

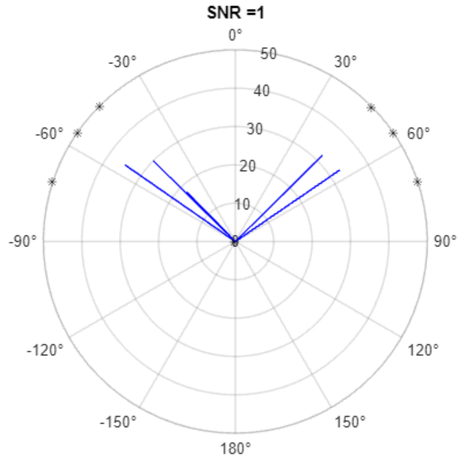

Fig. 7 Histogram for SNR = 1 dB after cleaning

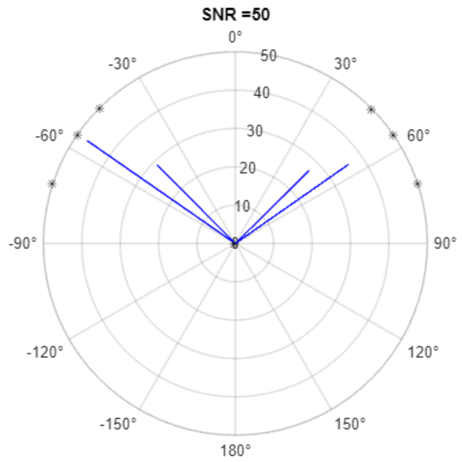

Fig. 8 Histogram for SNR = 50dB after cleaning

Average angular error as a function of SNR

To gain deeper insight into the influence of SNR on the accuracy of the DOA estimation, we plotted the average angular error of the determined directions as a function of SNR. This analysis aimed to reveal whether increasing noise levels significantly degrade the algorithm's performance or whether the method retains robustness across varying signal conditions.

Surprisingly, the results indicated that the average estimation error remains remarkably stable throughout the entire tested SNR range. Specifically, the error fluctuated only slightly between 0.006 and 0.0065 radians, showing no clear trend of deterioration with decreasing SNR. This consistency suggests that the MUSIC algorithm, even when operating on single-snapshot data, demonstrates a high degree of resilience to noise—delivering accurate DOA estimations even in relatively unfavorable conditions.

Such stability is especially valuable in practical applications, where required SNR levels cannot always be guaranteed. The findings support the conclusion that the proposed method is not only effective but also robust, making it suitable for deployment in real-world scenarios where signal quality may vary unpredictably.

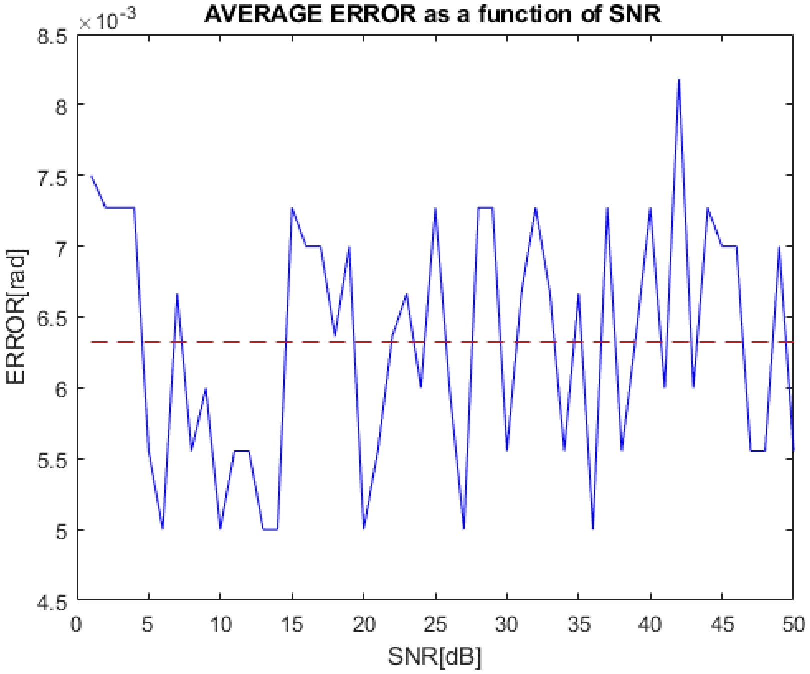

Fig. 9 Average error in rad as a function of SNR in dB

Estimation of signal paths

Utilizing the precisely estimated DOA values obtained across different SNR levels, we proceeded to reconstruct the most probable propagation paths of the signal toward the receiver. By projecting each identified DOA vector backward into the modeled environment and potential reflections, we were able to trace the signal's trajectory through the urban terrain. The fundamental assumption of this approach is that the point at which multiple backward-traced paths intersect corresponds to the location of the transmitter (TX).

To illustrate the effectiveness and reliability of this method, we present reconstructed path trajectories for two representative cases: one corresponding to the lowest tested SNR (1 dB) and the other to the highest (50 dB). These examples allow for a direct visual comparison of how noise levels impact the clarity and convergence of the signal paths. Despite the substantial difference in SNR, the reconstructed paths in both scenarios converge closely around the transmitter's true position, confirming the robustness of the proposed approach and the high precision with which the signal trajectories can be estimated—even under challenging noise conditions.

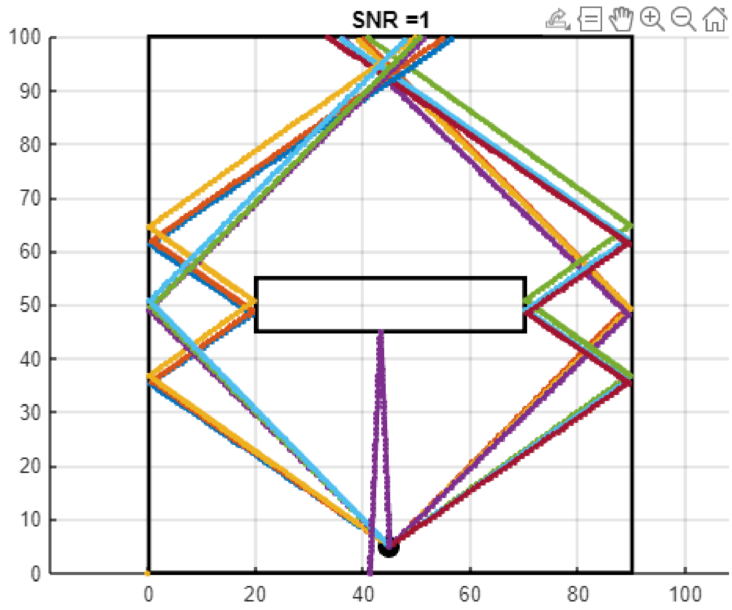

Fig. 10 Signal paths discovered for SNR = 1 dB

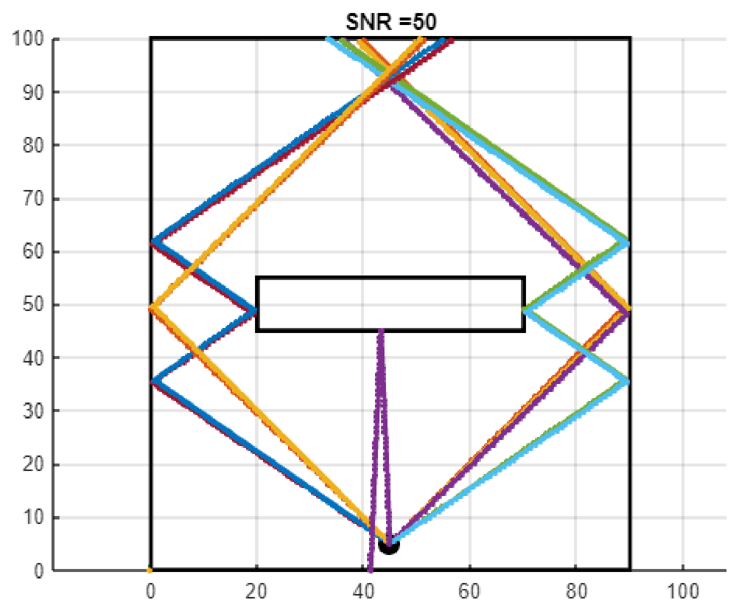

Fig. 11 Signal paths discovered for SNR = 50 dB

As evident from the reconstructed signal paths, the backward-projected DOA lines do not converge perfectly at a single point. Instead, due to minor estimation errors and variations introduced by noise, reflections, and discretization, they tend to intersect at multiple nearby locations, forming a cluster rather than a single intersection. This dispersion requires a post-processing step, to approximate the most probable location of the transmitter based on the distribution of all intersection points.

To address this, an averaging method was employed, where in the coordinates of all intersection points were computed and their centroid was taken as the final estimate of the transmitter's position. This simple yet effective approach yielded remarkably accurate localization results. In particular, for SNR values greater than 10 dB, the average localization error remained within approximately 3 meters. Notably, for higher SNRs, the average error decreased even further, ranging between 1 and 2 meters.

These results demonstrate that, despite the imperfect geometric convergence of the signal paths, the method is capable of delivering highly precise transmitter localization—underscoring its suitability for practical use in urban and multipath-dominated environments.

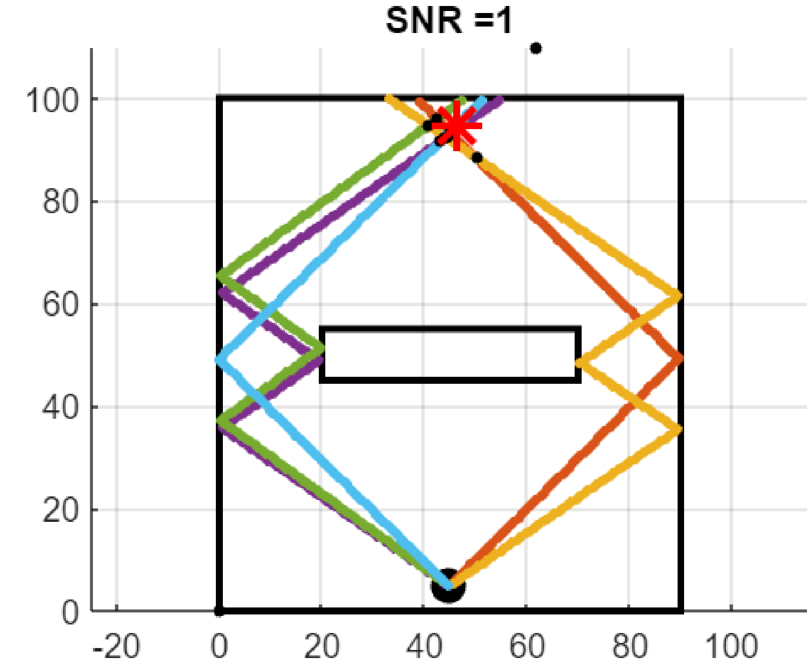

Fig. 12 Estimated localization for SNR = 1 dB

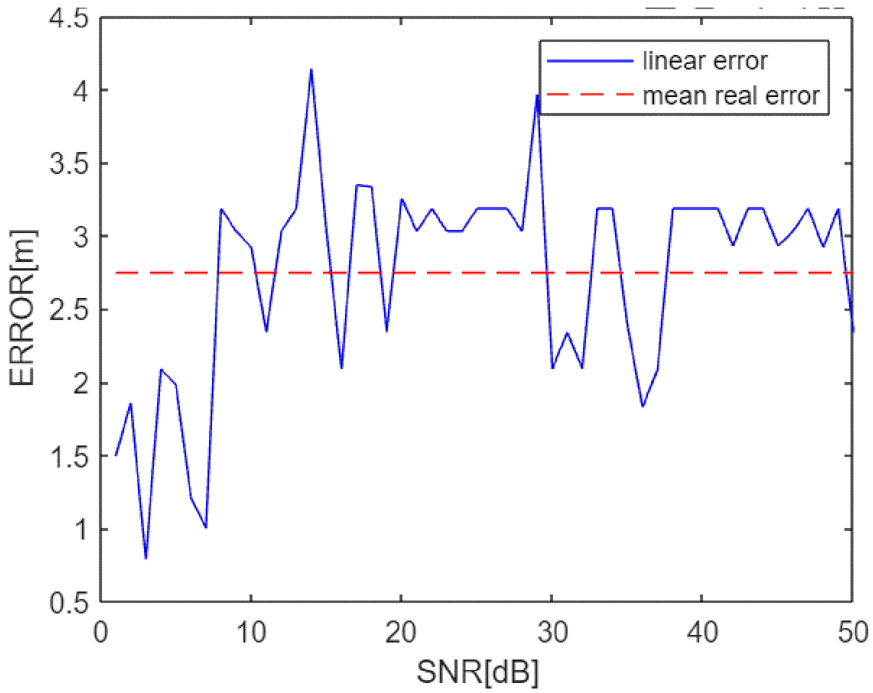

Fig. 13 Average linear error in SNR function

Upon examining the graph, a somewhat counterintuitive trend can be observed—namely, a slight decrease in localization error for lower SNR values. This suggests that the MUSIC algorithm maintains, or in some cases even improves, its performance in the presence of increased noise levels. One possible explanation lies in the well-documented robustness of the MUSIC algorithm when it comes to resolving multiple signal directions in noisy environments, particularly when signals remain sufficiently spatially distinct.

However, while this trend is intriguing, it should be interpreted with caution. The observed reduction in error at low SNR may also be influenced by other factors, such as the distribution of reflected paths, the specific geometry of the simulated environment, or statistical anomalies in the dataset. Therefore, a more comprehensive investigation potentially involving additional simulation scenarios, refined signal models, and deeper statistical analysis is required to fully understand the underlying causes of this phenomenon and to determine whether it holds consistently under broader conditions.

In summary, although the preliminary results are promising and highlight the potential strength of the MUSIC algorithm even in challenging noise conditions, further study is essential to validate and interpret these findings with confidence.

Discussion

The primary objective of this study was to investigate the feasibility of exploiting the multipath signal propagation for the localization of radio emission sources in urban environments. The results obtained from the conducted simulations clearly demonstrate that such an approach is not only theoretically sound, but also practically viable under certain controlled conditions. The successful reconstruction of signal paths and the relatively high localization accuracy, even in the presence of noise, indicates the potential of this method as an alternative or complement to traditional LOS techniques.

However, it is important to emphasize that this research represents an initial, exploratory step that will be followed by a comprehensive evaluation. The simulation environment used in this study was deliberately simplified for a controlled analysis of the method's core principles and capabilities, it did not account for the full range of complexities present in real-world urban scenarios, such as variable building materials, irregular geometries, dynamic obstacles, and environmental noise fluctuations.

To fully assess the practical applicability of the proposed localization method, further research is essential. This includes both the development of more advanced and realistic simulation environments as well as experimental validation through real-world measurements.

Conclusions

As a result of the conducted research on the localization of radio emission sources in urban environments through the exploitation of signal multipath propagation, several key conclusions can be drawn:

Methodological Potential: The study has shown considerable promise in the use of multipath signal propagation as a viable approach for localizing radio emission sources in complex urban settings. By analyzing reflected signal paths and employing advanced DOA estimation techniques such as the MUSIC algorithm, the method proved capability of accurately determining the directions of incoming signals, even in non-line-of-sight conditions.

Limitations of the Simulation Model: It is important to highlight that the simulation environment used in this research represented a simplified version of actual urban terrain. The model lacked the full structural and material diversity typically found in real-world urban environments, such as varied building geometries, surface materials, and dynamic obstacles. As such, while the results are promising, they must be interpreted within the context of these limitations.

Necessity for Further Investigation: To comprehensively evaluate the real-world applicability and robustness of this localization approach, further research is essential. This should include the development of more complex and realistic simulation environments, as well as empirical testing in actual urban settings. Such work will help assess how the method performs under varied and unpredictable conditions and whether its accuracy holds in practice.

Caution in Practical Implementation: While the current findings offer a solid foundation for future exploration, caution is advised when considering the direct application of the results to operational systems. Real-world deployment would require additional refinement of the algorithms, integration with other localization techniques, and rigorous validation under field conditions. Only then can the method be reliably used in critical applications.

Prospects for Development and Application: Despite the study's limitations, the findings open new possibilities for the advancement of localization technologies in urban environments. The method holds particular potential for applications in wireless systems monitoring, emergency response, and public safety systems.

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