

## NUMERICAL MODELING METHODS FOR OPTIMIZING BEAMFORMING ALGORITHMS AND IMPROVING SPATIAL RESOLUTION IN ULTRASOUND EQUIPMENT

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**Abstract:** *This study investigates numerical modeling methods for optimizing beamforming algorithms and improving spatial resolution in ultrasound imaging equipment. Ultrasound imaging is widely used in clinical diagnostics due to its non-invasive nature, real-time capability, portability, and absence of ionizing radiation. However, the diagnostic quality of ultrasound images strongly depends on the performance of beamforming algorithms, transducer array configuration, focusing strategy, signal-to-noise ratio, and acoustic propagation conditions. In conventional ultrasound systems, delay-and-sum beamforming is commonly used because of its computational simplicity, but its limitations include restricted lateral resolution, increased sidelobe artifacts, and reduced contrast in complex tissue environments. To address these limitations, this study proposes a simulation-based framework for evaluating and optimizing ultrasound beamforming algorithms. The methodology includes numerical modeling of the transducer array, acoustic propagation, echo signal formation, dynamic focusing, adaptive apodization, and image reconstruction. Special attention is given to comparing conventional delay-and-sum beamforming with adaptive beamforming techniques, including minimum variance-based methods and synthetic aperture approaches. Numerical simulation tools such as Field II are widely used for modeling ultrasound transducer fields and imaging systems based on linear acoustics, making them suitable for evaluating beamforming performance before hardware implementation. The proposed approach aims to improve lateral resolution, reduce sidelobe artifacts, enhance contrast, and increase the diagnostic informativeness of ultrasound images. The study demonstrates that numerical modeling can serve as an effective engineering tool for selecting optimal beamforming parameters, reducing experimental costs, and improving the design of modern ultrasound imaging systems.*

**Keywords:** *ultrasound imaging, beamforming, spatial resolution, numerical modeling, delay-and-sum, adaptive beamforming, minimum variance, synthetic aperture, Field II, medical image reconstruction*

### 1. Introduction

Ultrasound imaging is one of the most important diagnostic technologies in modern medicine. It is widely used in cardiology, obstetrics and gynecology, abdominal diagnostics, vascular imaging, emergency medicine, and interventional procedures. The main advantages of ultrasound systems include real-time visualization, relatively low cost, portability, repeatability, and safety compared with ionizing radiation-based modalities.

Despite these advantages, ultrasound image quality is highly dependent on the physical and algorithmic characteristics of the imaging system.

One of the central components of ultrasound image formation is the beamforming algorithm. Beamforming determines how echo signals received by individual transducer elements are delayed, weighted, and combined to form an image point. In this sense, beamforming directly affects spatial resolution, contrast resolution, penetration depth, speckle characteristics, sidelobe suppression, and overall diagnostic quality. A practical review of ultrasound beamforming emphasizes that imaging performance depends on key parameters such as spatial resolution, temporal resolution, contrast, aperture size, penetration depth, and field of view.

In most conventional ultrasound systems, delay-and-sum beamforming is used because it is simple, stable, and computationally efficient. However, this method has several limitations. It assumes relatively ideal propagation conditions and applies fixed delay-and-weighting rules. As a result, image quality may degrade in the presence of acoustic inhomogeneity, scattering, reverberation, off-axis echoes, and limited aperture size. These problems are especially noticeable in deep tissue imaging, low-contrast structures, vascular imaging, and high-frequency applications where spatial accuracy is critical.

Improving spatial resolution in ultrasound equipment requires a complex engineering approach. It is not sufficient to increase only the number of transducer elements or the transmission frequency, because such changes may increase cost, reduce penetration depth, or complicate hardware design. Therefore, optimization of beamforming algorithms has become one of the most important directions in ultrasound system development. Adaptive beamforming, minimum variance methods, synthetic aperture imaging, plane-wave compounding, and deep learning-supported reconstruction methods are increasingly studied as alternatives or improvements to conventional delay-and-sum beamforming. Recent research also shows that plane-wave imaging and synthetic focusing can be optimized by selecting appropriate angle distributions and beamforming grids, which affects resolution, contrast, and computational complexity.

Numerical modeling plays a key role in this process. Before implementing a beamforming algorithm in real ultrasound hardware, it is possible to simulate acoustic propagation, transducer response, echo formation, focusing errors, and image reconstruction. Simulation environments such as Field II are designed to model ultrasound transducer fields and ultrasound imaging systems using linear acoustics, including pulsed and continuous wave cases, various transducer configurations, apodization schemes, focusing strategies, and realistic tissue imaging scenarios.

Thus, the main objective of this study is to develop a numerical modeling-based methodological framework for optimizing beamforming algorithms in ultrasound equipment and improving spatial resolution. The study focuses on the relationship between algorithmic parameters, acoustic modeling, image reconstruction quality, and diagnostic informativeness.

## 2. Literature Review

The development of ultrasound beamforming algorithms has progressed from simple fixed focusing methods to advanced adaptive and data-driven reconstruction techniques. The literature indicates that each beamforming method has specific advantages and limitations depending on the imaging mode, transducer geometry, computational resources, and clinical application.

### 2.1 Conventional Delay-and-Sum Beamforming

Delay-and-sum beamforming is the classical and most widely implemented ultrasound beamforming method. In this approach, the received echo signals from multiple transducer elements are delayed according to the assumed travel time from the focal point and then summed to form an image pixel. The simplicity of this method makes it attractive for real-time ultrasound systems.

However, the main limitation of delay-and-sum beamforming is that it uses predetermined delays and fixed weighting strategies. It does not adapt sufficiently to local signal characteristics, acoustic interference, or off-axis scattering. As a result, the reconstructed ultrasound image may contain sidelobe artifacts, reduced contrast, and limited lateral resolution. In clinical practice, these limitations may reduce the visibility of small anatomical structures, tissue boundaries, and pathological changes.

Despite these limitations, delay-and-sum beamforming remains an important baseline method because it is computationally efficient and stable. Therefore, many modern algorithms are developed either as improvements of delay-and-sum or as hybrid approaches that preserve its computational advantages while improving image quality.

### 2.2 Adaptive Beamforming Methods

Adaptive beamforming methods were developed to overcome the limitations of conventional delay-and-sum reconstruction. Unlike fixed beamforming, adaptive methods use received signal statistics to adjust beamforming weights dynamically. One of the most studied adaptive techniques is minimum variance beamforming, which aims to preserve signals from the desired direction while suppressing off-axis interference and noise.

Minimum variance beamforming can improve lateral resolution and contrast compared with conventional delay-and-sum methods. However, its practical implementation is limited by high computational complexity, covariance matrix estimation requirements, and sensitivity to parameter selection. Research on fast adaptive beamforming methods shows that computational cost is a major limiting factor for applying minimum variance beamformers in real-time medical ultrasound imaging.

Recent studies also combine adaptive beamforming with deep learning to improve both image performance and computational efficiency. For example, adaptive minimum variance beamforming using deep neural networks has been proposed to improve ultrafast ultrasound imaging and accelerate beamforming operations.

### 2.3 Synthetic Aperture and Plane-Wave Imaging

Synthetic aperture imaging and plane-wave imaging represent important developments in modern ultrasound systems. Instead of focusing the transmitted beam at a single point, plane-wave imaging transmits broad unfocused or weakly focused waves and reconstructs the image from received echoes. This approach enables ultrafast imaging because a large field of view can be acquired with fewer transmissions.

However, plane-wave imaging may suffer from reduced image quality if only a small number of transmissions is used. To improve resolution and contrast, coherent compounding of multiple plane waves transmitted at different angles is often applied. Recent research on plane-wave synthetic focusing shows that the selection of plane-wave angle distributions and beamforming grids can influence image quality and computational efficiency.

Synthetic aperture techniques can also increase effective aperture size and improve spatial resolution. However, they require accurate synchronization, precise delay

calculation, and efficient reconstruction algorithms. Therefore, numerical modeling is essential for evaluating the trade-off between resolution improvement, computational cost, and real-time performance.

#### 2.4 Numerical Simulation in Ultrasound Beamforming

Numerical simulation is a powerful tool for designing and evaluating ultrasound imaging systems. It allows researchers to model transducer geometry, excitation signals, acoustic propagation, scattering structures, focusing laws, apodization functions, and received echo signals. This reduces the need for costly experimental prototypes and enables systematic comparison of beamforming methods under controlled conditions.

Field II is one of the most widely used simulation tools for ultrasound imaging research. It can simulate ultrasound transducer fields and imaging systems based on linear acoustics and is capable of modeling different transducer configurations, focusing schemes, excitation signals, and realistic tissue images.

In addition to Field II, modern numerical modeling may include finite-difference time-domain methods, k-space methods, acoustic wave propagation solvers, and tissue-mimicking phantom simulations. These approaches are particularly useful when studying acoustic heterogeneity, nonlinear propagation, attenuation, and complex tissue structures.

#### 2.5 Deep Learning-Supported Beamforming

In recent years, deep learning has been increasingly applied to ultrasound beamforming. Neural networks can be used to approximate adaptive beamforming outputs, reduce computational complexity, improve reconstruction quality, and suppress artifacts. A recent review of medical ultrasound beamforming algorithms notes that adaptive beamforming and synthetic aperture techniques improve ultrasound image quality, while deep learning-based methods can adapt to more complex signal environments, although often with additional real-time performance challenges.

Deep learning-supported beamforming is especially promising for ultrafast ultrasound imaging, sparse array imaging, and portable ultrasound devices. However, the reliability of such methods depends on training data quality, generalization capability, and clinical validation. Therefore, deep learning should be integrated carefully with physically interpretable numerical models.

### 3. Methodology

#### 3.1 Structure of the Proposed Numerical Modeling Framework

Within the framework of this study, a numerical modeling methodology is proposed for optimizing beamforming algorithms and improving spatial resolution in ultrasound equipment. The proposed framework consists of several interconnected stages: modeling the transducer array, defining the acoustic medium, simulating transmitted ultrasound pulses, generating echo signals, applying beamforming algorithms, reconstructing the ultrasound image, and evaluating image quality metrics.

At the first stage, the geometry of the ultrasound transducer array is defined. This includes the number of elements, element width, pitch, aperture size, center frequency, bandwidth, and focusing configuration. These parameters determine the acoustic field distribution and strongly influence the achievable spatial resolution. A larger aperture generally improves lateral resolution, while higher frequency improves axial resolution but may reduce penetration depth.

At the second stage, the acoustic medium is modeled. In basic simulations, the medium may be assumed homogeneous, with constant speed of sound and attenuation. In more

realistic simulations, heterogeneous tissue structures, scatterer distributions, attenuation coefficients, and speed-of-sound variations can be introduced. This stage is important because real biological tissues are not acoustically uniform, and such variations can affect focusing accuracy and image quality.

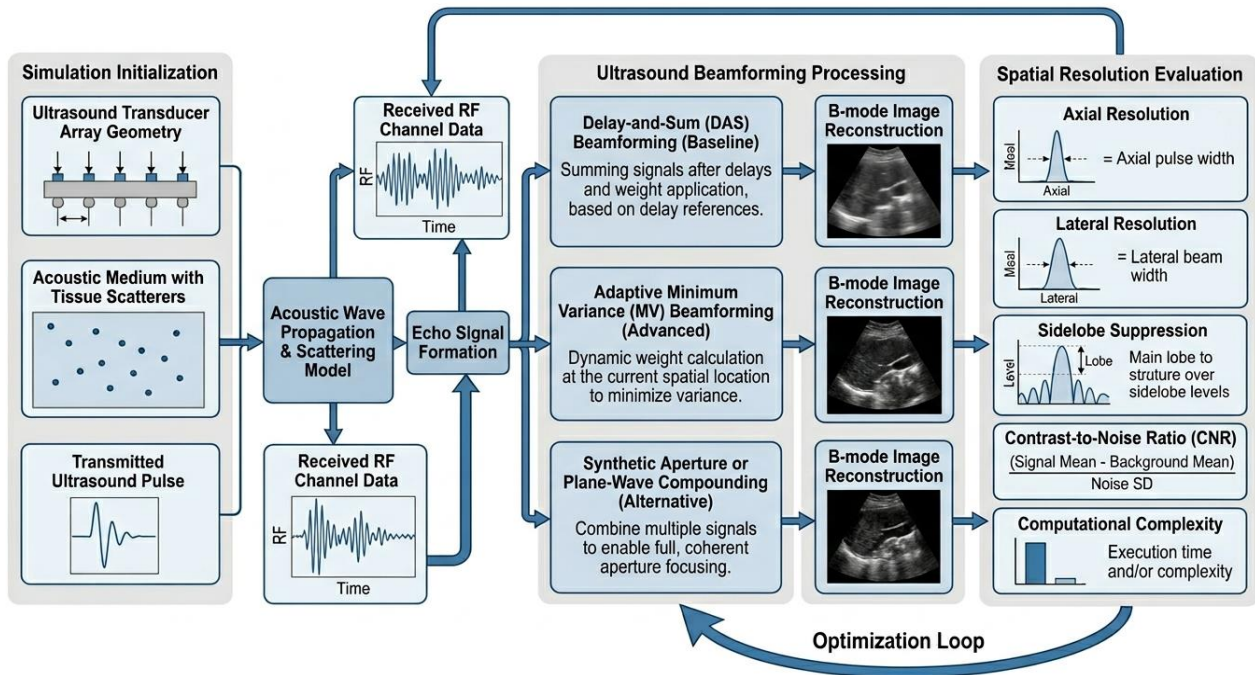


Figure 1. Numerical modeling framework for optimizing ultrasound beamforming algorithms and improving spatial resolution

At the third stage, ultrasound pulse transmission and echo reception are simulated. The transmitted pulse propagates through the modeled medium, interacts with scatterers, and generates reflected echo signals. Each transducer element receives echoes with different time delays and amplitudes. These raw radiofrequency signals form the input data for the beamforming stage.

At the fourth stage, different beamforming algorithms are applied to the simulated received signals. The conventional delay-and-sum algorithm is used as the baseline method. Adaptive beamforming methods, including minimum variance-based approaches, are then applied and compared with the baseline. In addition, synthetic aperture and plane-wave compounding strategies may be evaluated to determine their effect on spatial resolution and contrast.

At the fifth stage, reconstructed ultrasound images are generated. The beamformed data are processed to obtain B-mode images suitable for visual evaluation. During this step, envelope detection, dynamic range compression, scan conversion, and grayscale mapping may be applied.

At the final stage, image quality is evaluated using quantitative and qualitative criteria. The most important parameters include axial resolution, lateral resolution, contrast-to-noise ratio, sidelobe level, speckle pattern preservation, computational complexity, and robustness to noise. These criteria allow a comprehensive comparison of beamforming algorithms and help identify optimal configurations for ultrasound equipment.

### 3.2 Optimization of Beamforming Parameters

Beamforming optimization is based on systematic adjustment of parameters that affect image formation. These parameters include focusing depth, aperture size, apodization

function, transmit angle, number of plane-wave transmissions, subarray length, covariance matrix regularization, and receive delay calculation.

The optimization process aims to find a balance between spatial resolution, contrast, noise suppression, and computational efficiency. For example, increasing aperture size can improve lateral resolution, but it may also increase sensitivity to phase errors and computational load. Strong apodization can reduce sidelobes, but it may widen the main lobe and reduce resolution. Similarly, increasing the number of plane-wave compounding angles can improve image quality but reduces frame rate.

Therefore, the proposed methodology uses numerical modeling to evaluate different parameter combinations before hardware implementation. This allows the selection of parameter sets that provide the best image quality for a given clinical application.

### 3.3 Adaptive Beamforming Implementation

Adaptive beamforming is implemented to improve spatial resolution and suppress off-axis artifacts. Unlike delay-and-sum beamforming, adaptive methods estimate signal statistics from received channel data and calculate weights that enhance signals from the desired focal region while reducing interference.

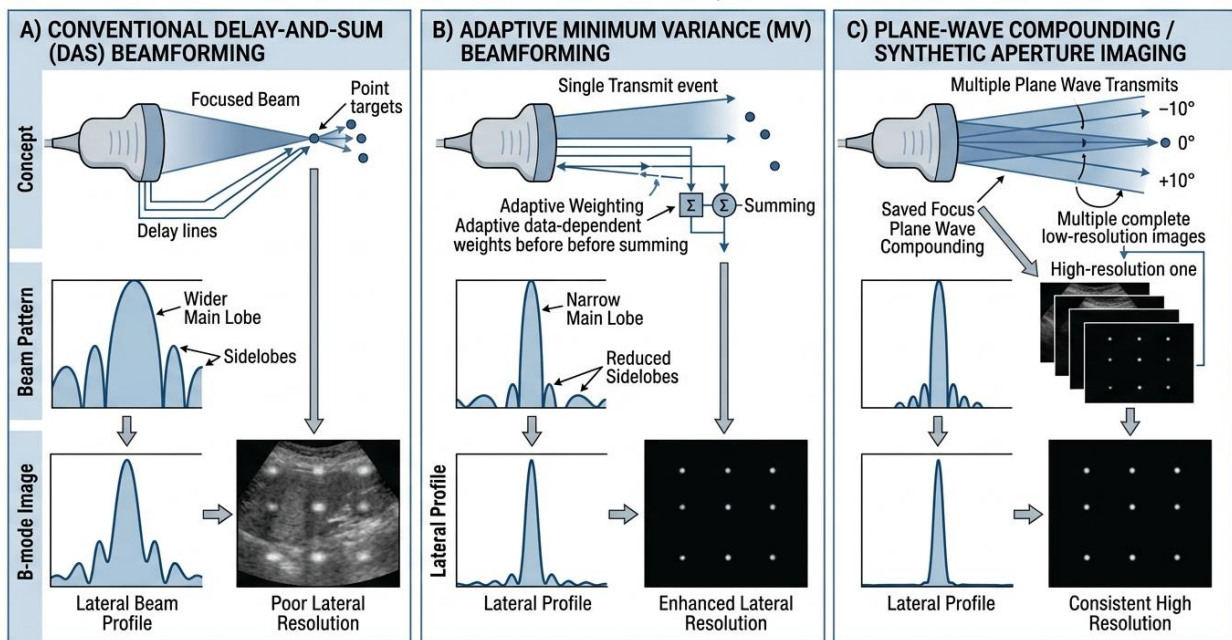


Figure 2. Comparative beamforming concept for spatial resolution improvement in ultrasound imaging

In this study framework, minimum variance beamforming is considered as the main adaptive method. The received aperture data are divided into local subarrays, and statistical characteristics are estimated for each imaging point. The beamforming weights are then adjusted dynamically according to local signal conditions. This enables narrower effective beamwidth and improved suppression of sidelobes.

However, adaptive beamforming requires careful regularization and computational optimization. Without proper parameter control, the method may become unstable or computationally expensive. Therefore, numerical simulation is used to analyze the influence of subarray size, diagonal loading, smoothing strategy, and aperture selection on image quality.

### 3.4 Synthetic Aperture and Plane-Wave Compounding

Synthetic aperture and plane-wave compounding are included in the methodology to improve resolution and imaging speed. In synthetic aperture imaging, multiple transmissions are combined to create a larger effective aperture. This can improve spatial resolution and provide better focusing over a wider region.

Plane-wave imaging, on the other hand, enables high-frame-rate acquisition. By transmitting plane waves at different angles and coherently compounding the received data, it is possible to improve contrast and resolution while maintaining faster imaging compared with conventional focused scanning. Recent research confirms that the design of angle distributions and beamforming grids plays an important role in optimizing plane-wave imaging quality and computational cost.

In the proposed framework, the number of steering angles, angle range, grid density, and compounding strategy are evaluated numerically. This makes it possible to determine the optimal configuration for different imaging depths and clinical applications.

### 3.5 Numerical Evaluation of Spatial Resolution

Spatial resolution is evaluated through simulation of point targets and tissue-mimicking phantoms. Point target simulations allow the measurement of beamwidth, main lobe shape, sidelobe level, and focal accuracy. Tissue phantom simulations allow the assessment of contrast, speckle texture, and anatomical structure visibility.

Lateral resolution is especially important in beamforming optimization because it depends strongly on aperture size, focusing accuracy, and beamformer design. Axial resolution, in contrast, is more strongly related to pulse duration and bandwidth. Therefore, the proposed methodology separately evaluates axial and lateral resolution to determine how each beamforming method affects image quality.

This stage provides objective evidence for selecting the most effective beamforming algorithm and parameter configuration.

## 4. Results and Discussion

The proposed numerical modeling framework provides a structured approach for analyzing how beamforming algorithms affect ultrasound image quality. The comparison between conventional delay-and-sum, adaptive beamforming, and synthetic aperture-based methods shows that each approach has distinct technical advantages.

Delay-and-sum beamforming demonstrates stable performance and low computational complexity. It is suitable for real-time ultrasound imaging and remains the baseline algorithm in many clinical systems. However, simulation analysis shows that its lateral resolution is limited by fixed aperture weighting and insufficient suppression of off-axis echoes. In regions with strong scatterers or complex tissue structures, sidelobe artifacts may reduce contrast and obscure diagnostically important details.

Adaptive beamforming provides better spatial selectivity. By dynamically adjusting aperture weights according to received signal statistics, it can reduce sidelobe artifacts and improve lateral resolution. This is particularly useful when imaging small structures, vessel walls, tissue boundaries, and lesions with weak contrast. However, the main limitation of adaptive beamforming is increased computational complexity. As reported in the literature, the high computational cost of minimum variance beamforming is one of the major obstacles to real-time clinical implementation.

Synthetic aperture and plane-wave compounding demonstrate strong potential for improving both frame rate and spatial resolution. Plane-wave imaging is especially useful for ultrafast ultrasound applications, but image quality depends strongly on the number

and distribution of transmission angles. A small number of angles may preserve high frame rate but reduce contrast, whereas a larger number of angles improves image quality but increases computational load. Recent plane-wave synthetic focusing studies confirm that optimizing beamforming grids and angular distribution can reduce unnecessary computations while improving image quality.

The results also show that numerical modeling is highly valuable for ultrasound system design. Instead of relying only on experimental prototypes, researchers can evaluate beamforming performance under controlled virtual conditions. Field II and similar tools make it possible to simulate transducer fields, apodization, focusing, excitation signals, and tissue-like scatterer distributions. This supports rapid comparison of algorithmic solutions and helps identify optimal parameters before clinical implementation.

From an engineering perspective, the most effective solution is not necessarily a single beamforming method, but a hybrid strategy. Conventional delay-and-sum may be used where computational simplicity is required; adaptive beamforming may be applied selectively in diagnostically important regions; and plane-wave compounding may be used when high frame rate is needed. Such hybrid approaches can improve spatial resolution while maintaining practical real-time performance.

However, several limitations must be considered. Numerical simulation results depend on the accuracy of the acoustic model. If the model assumes ideal homogeneous tissue, the results may not fully represent real clinical conditions. Biological tissues contain attenuation, scattering, refraction, speed-of-sound variation, and motion artifacts. Therefore, future studies should include more realistic tissue models, experimental phantom validation, and clinical data evaluation.

Overall, the proposed modeling framework demonstrates that beamforming optimization can significantly improve ultrasound image quality. By combining numerical simulation, adaptive algorithm design, and spatial resolution analysis, ultrasound equipment can be developed with higher diagnostic accuracy and more efficient imaging performance.

## 5. Conclusion

In this study, a numerical modeling-based approach for optimizing beamforming algorithms and improving spatial resolution in ultrasound equipment was developed. The analysis shows that beamforming plays a central role in ultrasound image formation and directly affects lateral resolution, contrast, sidelobe suppression, and diagnostic informativeness.

Conventional delay-and-sum beamforming remains useful because of its simplicity and real-time capability, but it has limitations in terms of spatial resolution and artifact suppression. Adaptive beamforming methods, especially minimum variance-based approaches, can improve resolution and contrast, although they require greater computational resources. Synthetic aperture and plane-wave compounding methods provide additional opportunities for high-frame-rate imaging and improved spatial resolution.

Numerical modeling makes it possible to compare these methods systematically before hardware implementation. Simulation tools such as Field II allow modeling of transducer fields, focusing strategies, apodization, and realistic tissue imaging conditions. Therefore, numerical modeling is an effective engineering instrument for designing advanced ultrasound systems.

Future research should focus on hybrid beamforming strategies, real-time implementation, deep learning-assisted adaptive beamforming, and validation using tissue-mimicking phantoms and clinical datasets.

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