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Obstacle-Aware Proactive Beam Management Based on Real-Time Ray Tracing for mmWave Networks

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***Abstract*—The increasing demand for efficient millimeter-wave (mmWave) beam management in wireless communication systems of 5G, 6G and beyond necessitates innovative approaches to mitigate the resource-intensive and latency-prone nature of exhaustive search methods. This paper presents a novel approach leveraging FPGA-accelerated real-time ray tracing for dynamic beam management. The proposed method dynamically reduces the number of beam directions and burst periodicity based on the mobility and density of mobile devices, as well as the presence of obstacles and available propagation paths. By utilizing a digital twin and real-time ray tracing, the system estimates the required beam directions, enabling adaptive beam management that allows to respond to dynamic obstacles and user mobility. The efficacy of the proposed methodology is showcased in an initial vehicular logistics scenario and can be transferred to further scenarios like intelligent transportation systems and others. Within the sample scenario, the resource overhead is reduced to roughly a third, while the utilization of the base station antenna's beamforming gain is significantly improved.**

***Index Terms*—6G, mmWave, beam management, real-time ray tracing, digital twin, vehicular networks.**

I. Introduction

Since the Fifth Generation of Mobile Communications (5G), the so–called Millimeter-Wave (mmWave) spectrum is usable and offers high bandwidths but hostile radio conditions. A key principle for its utilization arises from the need for directional communications by means of antenna arrays. The directivity can be understood as a beam pointing in a certain direction and thus enabling amplification of a selected signal propagation path. However, suitable signal propagation paths need to be explored using the so–called exhaustive search procedure. This is a lengthy and time–consuming approach of sweeping the beam comprehensively through the antenna's coverable angular search space and may need to be revised for the Sixth Generation of Mobile communications (6G).

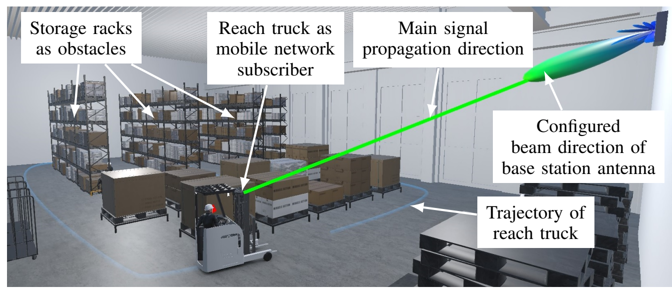

Fig. 1: Sample applications of proposed enhancement on beam management: In an intra–logistics scenario, a digital twin with real–time ray tracing determines propagation paths to efficiently connect a reach truck to the mmWave network.

This work presents a digital twin–based concept of reducing the required search space of this established procedure by means of real–time ray tracing enabled context–awareness. This means, that environmental information (reflection surfaces, obstacles, ...) is forwarded to a digital twin and processed in real–time to analyze signal propagation paths for given mobile device trajectories and distribution areas. Fig. 1 illustrates this with an example for an intra–logistics application use case. In conjunction with the dynamic exploration of possible signal propagation paths, this work aims to increase the efficiency of the exhaustive search procedure by purposefully reducing the search space and thus accelerating the beam sweeping process. As results show, plenty of beam directions are not relevant e.g. for typical warehouse scenarios and can be omitted to make the exhaustive search more efficient and resource–saving on the one hand. On the other hand, standard configurations such as beam directions in a grid structure can be discarded in favor of an optimized configuration of beam directions tailored for the respective scenario. That way, the beamforming gain of the base station antenna can be used more advantageously resulting in improved coverage.

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The remainder of the paper is structured as follows: After an overview and a discussion on related work in Sec. II, the system architecture as well as the proposed procedure is covered in Sec. III. The approach is then evaluated for a sample scenario in Sec. IV, before Sec. V closes with a conclusion and an outlook.

II. Related Work

Efficient beam management is critical for enabling the high data rates and low latency required by mmWave communication systems. Traditional approaches to beam management often rely on exhaustive search techniques, where the entire angular search space of the antenna is swept to identify optimal beam directions. While effective in ensuring robust communication, these methods incur significant latency and computational overhead, especially when narrow beams are employed. The authors in [1] have analyzed the exhaustive search approach under varying system parameterizations, focusing on three key performance metrics: Detection accuracy, reactiveness, and overhead.

To address the limitations of classical methods, context–aware beam management has emerged as a promising solution. This technique leverages environmental information, such as user location and obstacle positions, to narrow the search space. For instance, a multilevel beam search procedure using user location information was shown in [2] to reduce beam scanning time while maintaining robust performance even in the presence of location inaccuracies. Another approach [3] employs depth sensors to dynamically detect human shadowing and adapt beam directions to the best reflected path based on ray tracing, enhancing reliability in obstructed scenarios. Additionally, recent advancements [4] utilize LIDAR data combined with neural networks for efficient beam selection in mmWave Vehicle–to–Infrastructure (V2I) scenarios, achieving near–optimal performance without exhaustive beam search. Furthermore, spatial information combined with Extended Kalman Filter (EKF) has been used in [5] to improve beam tracking accuracy, especially in high–mobility scenarios, by effectively integrating sensor data with beam training signals.

Digital twin technology has recently gained traction in wireless communication, offering a virtual replica of the physical environment for real–time simulation and optimization. A comprehensive survey has been done in [6], highlighting the potential of digital twins integrated with Artificial Intelligence (AI) to optimize 6G networks. Specifically, for Reconfigurable Intelligent Surface (RIS)–aided communication, digital twins can approximate wireless channels through electromagnetic modeling and ray tracing, reducing the reliance on direct channel estimation and enhancing interference management [7].

This work proposes a novel integration of FPGA–accelerated real–time ray tracing as proposed in previous works [8], [9] with a digital twin to enable adaptive beam management. By dynamically adjusting beam directions based on mobility patterns and obstacle presence, the proposed approach bridges the gap between context–awareness and real–time adaptability, providing a scalable solution for next–generation wireless networks.

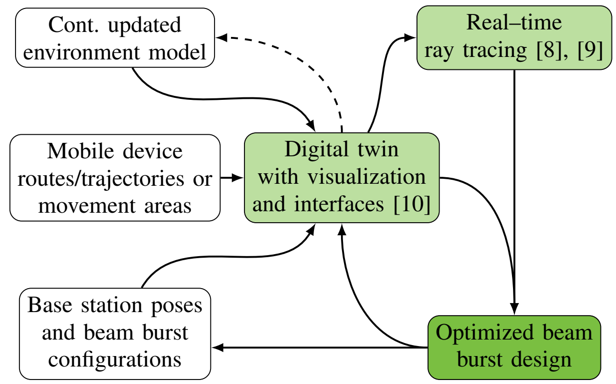


Fig. 2: System model for digital twin and real-time ray tracing aided beam management.

III. Methodology

The concept is implemented by merging prior works and extending them by an obstacle–aware proactive beam management approach. On the one hand, the digital twin structure as proposed in [10] is utilized as framework for extending existing and integrating new components. On the other hand, the real–time ray tracing implementation as detailed in [8], [9] drives the simulation and exploration of radio propagation paths. Accordingly, the system model is illustrated in Figure 2, where the digital twin forms the central part and is complemented by the newly added real–time ray tracing component for discovering propagation paths.

For building up the digital twin, appropriate environment models are essential. It is believed, that, e.g., for indoor applications like logistics or production facilities, floor plans or even three-dimensional (3D) models are generally available or can be gathered autonomously by means of any kinds of (human–operated or) autonomous material handling equipment like Autonomous Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs). Even the wireless communication itself may be suited to build up an environmental model as research works like [11], [12] stress.

Similarly, AGVs need to locate themselves as well as their transported goods and thus can also be considered as moving obstacles or passive reflectors within the scene. It is assumed that such information is also available in the digital twin, so there is a continuously updating geometric environment model.

This 3D model serves as data source for real–time ray tracing analyses. It is processed and compressed to principal components to further accelerate computations as detailed subsequently.

While base station poses may be fixed and known to the digital twin, not only the current positions of the material handling equipment (as participants in the mobile network) are forwarded to the digital twin, but also their planned routes or trajectories. Even if this knowledge was not dynamically obtainable in real–time, bounding areas could be defined, where the mobile network subscribers could generally be encountered. Typically, ray tracing is performed on a rasterization of such areas and provides details on signal propagation paths for each grid point of the rasterized area.

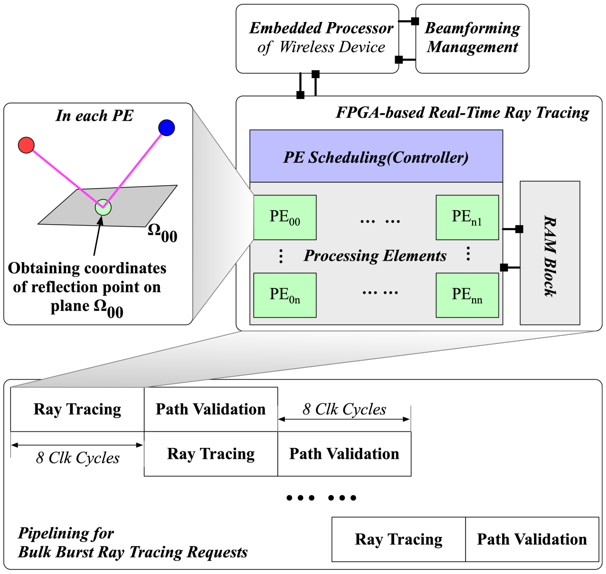


Fig. 3: Overview of the real–time ray tracing platform on FPGA: Each processing element PE implements geometrical calculation of a reflection plane. Intermediate results in each round of iteration are buffered by on–chip RAM block. By scheduling the execution order of each PE, the ray tracing can be well organized.

Based on this information, the digital twin is primarily able to derive valuable insights into the network coverage based on a given set of beam directions. Additionally, such beam direction dependent insights can even be used to improve the beam management by optimizing the set of beam directions and finally the network coverage in terms of signal strength as well as radio resource utilization.

Real–time ray tracing

The real–time ray tracing method is capable of achieving parallel acceleration of ray tracing simulations [8]. This is accomplished by transforming the 3D model of the target environment into hardware modules implemented on Field Programmable Gate Array (FPGA) with the aim of achieving the iterative computation of the first three orders of reflection paths for signal propagation within milliseconds [9]. The architecture of the real–time ray tracing module implemented on FPGA is illustrated in Figure 3.

The processing elements of this module are responsible for performing geometrical computations involving the corresponding reflection planes. Meanwhile, the scheduling module is rationally organized in order to achieve the iterative convergence of the shortest make–span in ray tracing simulation. Only considering direct paths and first order reflections may even allow for omitting the scheduling further reducing the processing time. Additionally, bulk requests, i.e. results for many different mobile device positions are handled using pipelining to further increase efficiency.

A *snapshot* of the current scenario given by the environment model can be handled through the FPGA–based real–time ray tracing to discover usable signal propagation paths. The optimal signal propagation path can then be obtained by filtering the paths according to a given criterion (e.g., shortest path length), and the beam steering angle corresponding to this path is passed to the beam management unit for further configuration and processing. Even a forwarding of all possible paths to the beam management unit is conceivable to defer the path selection e.g. for multiple User Equipments (UEs). That way, further optimizations like minimizing the number of different beam directions can be performed at the beam management unit by sacrificing gain from ideal beam alignment as well as received power by not necessarily selecting the shortest path.

In dynamic scenes, motion patterns/trajectories are taken into considerations in the ray tracing for adapting the beam burst design, i.e. the set of base station beam directions. Additionally, the blocking effect of dynamic obstructions can be adequately simulated concurrently. Deriving the potential trajectories of a dynamic blocker is possible by employing routing algorithms, such as *safe artificial potential field* algorithm from [13]. This process yields a set of predicted trajectories, which are then analyzed using Monte Carlo methods to determine the impact of the dynamic blocker on signal propagation facilitating the generation of a highly robust beam steering pattern for beam management.

In addition, model uncertainties and modeling errors must be taken into account in the design process and kept to a minimum through constant comparison with reality. Thus, the digital twin may continuously adjust parameters of the environmental model or how ray tracing results are derived from it. That way, our design is generally able to refine itself recursively during run time. However, the implementation of a feedback/refinement loop will be addressed in future work.

Design of beam management routine

Utilizing the proposed system model, the digital twin is able to cater for an information flow as depicted in Figure 4. This allows for the implementation of beam management procedures focusing on a dynamic design of proper beam bursts as detailed in the following.

Since the base stations need to supply the mobile devices along those routes or within those areas with reasonable mobile network coverage, the ray tracing solution is able to reveal usable signal propagation paths and their corresponding Angle of Departures (AoDs) from the base stations. With this, the beam directions to be set per base stations are determined and mapped to those routes or areas of the mobile devices.

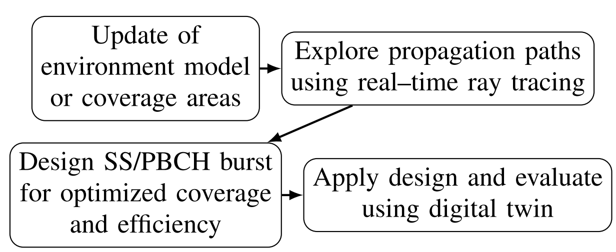


Fig. 4: Overview of the proposed dynamic SS/PBCH burst design for overhead reduction and mobility support improvements.

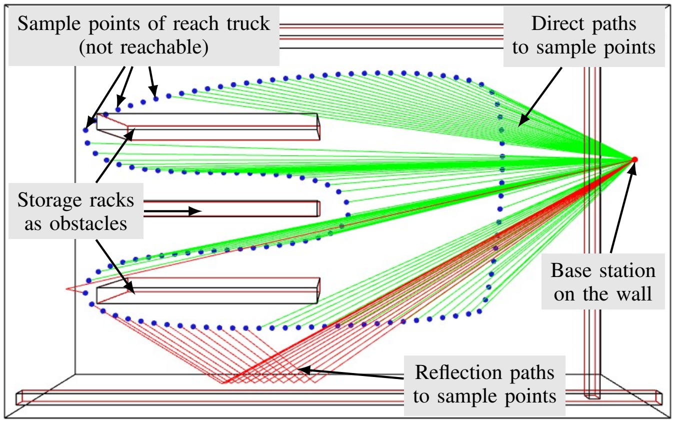


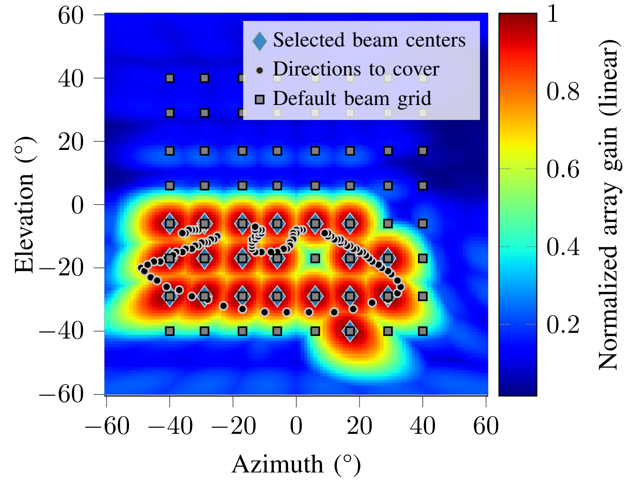
Fig. 5: Top view on a simplified 3D model of the intra–logistics scenario from Fig. 1 with highlighted paths between base station and sample positions of mobile device.

According to 5G specifications [14], the number of different beam directions within the Synchronization Signal/Physical Broadcast Channel (SS/PBCH) burst is limited. In principle, it is obvious that the basic concept must also be retained for 6G in order to be able to offer broadcast channels despite directional transmissions. While a comprehensive coverage with wide beams and many different beam directions seems to be an acceptable solution, subsequent analyses will show, that drastic efficiency gains in terms of signal strength as well as radio resource utilization are achievable.

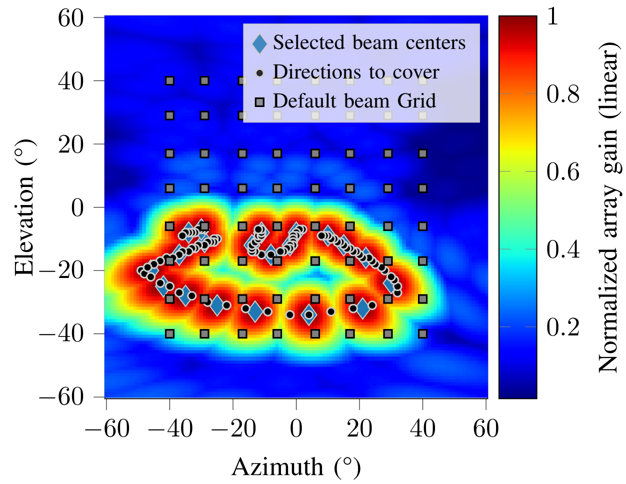
Depending on the used antenna array, it may either allow for a selection of non–overlapping beams from a predefined code book or for a fine–grained adjustment of the beam's azimuth and elevation angle. In any case, the conceived beam burst design translates the set of ideal beam directions into a SS/PBCH burst structure consisting of a limited number of SS/PBCH blocks. These blocks use different beam directions to spread the broadcast signal accordingly. Finally, the proposed automated design process caters for a reasonable trade–off between a comprehensive network supply to all the possible mobile device positions along the given routes or within the defined areas and the signaling overhead due to the number and rate of SS/PBCH blocks.

IV. Evaluation

In order to evaluate the proposed approach, a case study is carried out in the context of a logistics hall scenario as depicted in Figure 1. While there is a base station on the wall, coverage in the hall is partially hampered by objects such as storage racks. Logistics may be carried out using reach trucks, which are wirelessly connected to the network infrastructure. Their movement area is predefined and known for the study. Fig. 5 presents a simplified 3D model of the sample scenario, which is forwarded to the real–time ray tracing implementation. The ray tracing discovers available paths to each sampled point of the movement area within about 320 ns including path validation per point (assuming a default 50 MHz clock rate). For processing many points, parallelization by an increased usage of FPGA resources is conceivable, if the duration of consecutive processing appears not to meet the requirements.



(a) Only 20 of 64 beams utilized from the default beam grid, i.e. substantial reduction of SS/PBCH burst size at no cost.



(b) Optimizable placement of beams to improve the array gain along the directions that emerged from the sampled trajectory.

Fig. 6: Adaption of beam burst structure to mobile devices' mobility. The black circles depict the ideal beam directions to the sampled trajectory points from Figure 5. A beam burst structure may optimize coverage along the trajectory while reducing the required amount of beams compared to a default grid structure as indicated by gray squares.

The resulting shortest paths are depicted as green and red lines for direct and first order reflected paths, respectively.

Direction information from the base station antenna's perspective can be used for adapting the SS/PBCH burst structure or beam directions used therein. A default burst structure could be given by a regular grid for comprehensive coverage as depicted as gray squares in Figure 6a. This aligns with a predefined code book for a fixed number of applicable beam directions. However, the ray tracing results reveal, that only a third of those beam directions would ever be active in the given scenario. Thus, the unused directions could be selected less frequently or removed completely from the SS/PBCH burst to reduce its signaling overhead. The aggregated gain

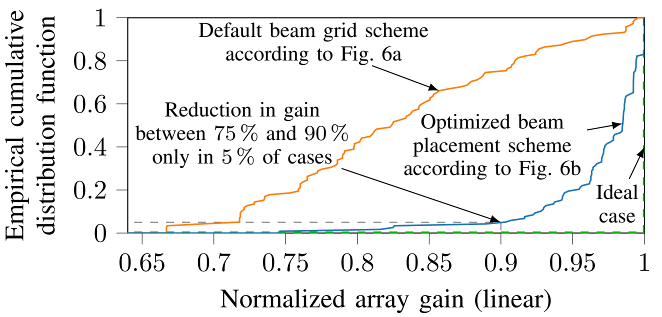


Fig. 7: Distribution of the aggregated antenna gain along the sampled points of the mobile device trajectory.

of the selected beam directions of the phase shift beamformer is shown as color gradient in the background.

The gain along the mobile device trajectory or within its movement area could be further optimized by moving the beam centers and/or changing their amount. For example, an initial approach based on k–means clustering is applied in Figure 6b, using as many clusters as there are identified useful beams in the grid–based approach from Figure 6a. The aggregated gain representation is adjusted accordingly and the impact on the signal quality in terms of higher usable antenna gains is evaluated subsequently. While this work focuses on the general approach of integrating real–time ray tracing into a dynamic and environment–aware beam management design, optimizations with a more nuanced view on appropriate constraints will be evaluated in future work.

Finally, Figure 7 shows the performance of the initial optimization approach compared to a conventional grid–based SS/PBCH structure without knowledge of the scenario and mobile device movement area. A conventional grid–based approach with a limited amount of predefined beam directions suffers from a higher share of beam misalignments, while optimized/fitted solutions (depending on constraints) are able to improve the coverage significantly and simultaneously reduce the signaling overhead. With as many different beam directions as used in a grid–based design, the distribution of array gain along the sampled trajectory points (blue line) highlights the potential of the proposed concept.

V. Conclusion

Beam management is a key component of current and upcoming mobile/vehicular networks utilizing directional communications by means of array antennas. However, the exploration of suitable signal propagation paths to the mobile device introduces signaling overhead, which can be significantly reduced as proposed in this work.

The digital twin approach draws on current environmental information of the base station's vicinity to apply a real–time ray tracing enabled exploration of signal propagation paths. That way, context–awareness is introduced to dynamically adapt the configuration of the exhaustive search making it more efficient and resource–saving. In addition to a reduced signaling overhead, also a continuous provision mobile network coverage can be maintained even at higher mobilities of mobile devices due to the accelerated update rates of relevant beam directions. Applying optimizations to the code book or beam directions tailored to the discovered propagation paths and intended overhead drastically improves the antenna array's experiential beamforming gain within the mobile device movement area. Results of the implemented digital twin–based simulation study demonstrate the applicability and drastic advantages for a sample warehouse scenario.

In future work, the assumed given environmental knowledge will be gathered by means of state–of–the–art concepts relying on image processing and laser scans. Further, the proposed approach will be evaluated by means of real–world studies in our experimental hall as well as outdoor vehicular scenarios.

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