Ref. Ares(2025)7006926 - 29/08/2025

Holden Deliverable

D4.5 – Application to a Wifi compliant beam-steering technology

Grant Agreement number	101099491
Action Acronym	HOLDEN
Action Title	Ehtical Design of Holography with Dense wireless Networks
Type of action	HORIZON-EIC-2022-PaTHFINDEROPEN-01
Version date of the Annex I against which the assessment will be made	13/12/2022
Start date of the Project	1/6/2023
Due date of the delierable	31/08/2025
Actual date of submission	29/08/2025
Lead beneficiary for the deliverable	AALTO
Dissemination level of the deliverable	Public

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Change history				
Version	**Date**	**Status**	**Partner**	**Description**
1.0	24.08.2025	Final	Aalto	First final draft
2.0	25.08.2025	Final	CNR	Second final draft
3.0	25.08.2025	Final	AALTO	Final version

Abstract

This deliverable explores the application of WiFi-compliant beam-steering technology (D4.2 and D4.3) to enable privacy-centric Radio Frequency (RF) sensing within the HOLDEN project, which aims to advance ethical and privacy-compliant ubiquitous perception. By leveraging directional signal focusing in IEEE 802.11 standards, such as 802.11ax and 802.11ad/ay, beam-steering enhances localization, tracking, and activity recognition for applications in smart living, logistics, and free-space interaction. The survey consolidates technical advancements, including phased array antennas, hybrid beamforming, and channel state information processing, alongside ethical considerations to ensure compliance with privacy-by-design principles and regulatory frameworks like GDPR. The document is structured to review state-of-the-art technologies, address privacy and security challenges, and propose solutions aligned with HOLDEN's goals of continuous-space holographic processing, discrete-space beamforming, and high-dimensional tensor processing. This work highlights the transformative potential of WiFi-based RF sensing in creating scalable, cost-effective, and ethically sound solutions for next-generation smart environments. The work lays the foundation for the testing and benchmarking activities of the beamsteering system inside the ADANT testhouse environment, which will be conducted in WP6 and in the next deliverables.

Contents

1 Introduction

The HOLDEN project represents a pioneering effort to advance ubiquitous perception through Radio Frequency (RF)-based sensing, enabling transformative applications in smart living, automated logistics, and free-space gesture interaction. By leveraging distributed multi-antenna systems, HOLDEN aims to achieve unprecedented accuracy in simultaneous multitarget recognition while prioritizing ethical compliance and privacy preservation. Unlike traditional RF-sensing approaches, which often prioritize technological performance over societal impact, HOLDEN adopts a privacy-centric paradigm, integrating ethical constraints and privacy-by-design principles from the outset. This deliverable explores the application of WiFi-compliant beam-steering technology as a cornerstone for realizing HOLDEN's vision, addressing both technical and ethical challenges in RF-based perception.

WiFi-compliant beam-steering technology refers to the use of directional signal focusing within standardized WiFi protocols, such as IEEE 802.11ax and 802.11ad/ay, to enhance RF sensing capabilities. By dynamically controlling the direction of RF energy, beam-steering enables precise localization, tracking, and activity recognition, making it a critical enabler for HOLDEN's goal of ubiquitous perception. This technology leverages existing WiFi infrastructure, offering cost-effective and scalable solutions for applications ranging from smart homes to logistics hubs. However, its potential to capture detailed spatial and behavioral data raises significant privacy and ethical concerns, necessitating a careful balance between functionality and user protection.

While significant advancements have been made in Multiple-Input Multiple-Output (MIMO) and massive MIMO technologies, their integration into privacy-centric sensing systems remains underexplored. This document consolidates current research, identifies gaps in technical and ethical frameworks, and proposes solutions that align with HOLDEN's privacy-by-design ethos (D4.3). By synthesizing insights from RF engineering, signal processing, and ethical studies, this deliverable aims to provide a comprehensive foundation for developing privacy-compliant sensing technologies.

The objectives of this deliverable are threefold: first, to review the state-of-the-art in WiFi-compliant beam-steering technologies, focusing on their applicability to RF-based sensing; second, to evaluate ethical and privacy constraints, ensuring alignment with regulatory frameworks like General Data Protection Regulation (GDPR) and ethical Artificial Intelligence (AI) principles; and third, to align proposed solutions with HOLDEN's three complementary paths: continuous-space measurement points via holographic image processing, discrete-space measurement points through advanced 3D beamforming, and high-dimensional tensor processing for complex activity recognition. These paths collectively address the technical and ethical challenges of ubiquitous perception, paving the way for innovative, privacy-respecting applications.

In the broader context, the HOLDEN project responds to the growing demand for ubiquitous perception in an era defined by the Internet of Things (IoT), 5G, and smart environments. RF-based sensing, enhanced by WiFi-compliant beam-steering, offers non-intrusive solutions for addressing global challenges, such as supporting aging populations through health monitoring, optimizing urban logistics, and enabling seamless human-computer interaction. Unlike camera-based or wearable technologies, WiFi-based sensing operates effectively in diverse environments—indoor, outdoor, urban, and rural—without requiring line-of-sight or user-worn devices. This versatility positions HOLDEN at the forefront of next-generation connectivity and perception, aligning with emerging trends like 6G, edge computing, and AI-driven sensing.

HOLDEN's interdisciplinary approach integrates RF engineering, data science, ethics, and user experience design, fostering collaboration among academia, industry, and policymakers. This synergy ensures that technological advancements are both practically viable and ethically sound. By leveraging existing WiFi infrastructure, HOLDEN's beam-steering solutions promise scalability and cost-effectiveness, potentially redefining automation and interaction paradigms across industries. The transformative potential of this work lies in its ability to deliver precise, privacy-compliant sensing that empowers users while safeguarding their autonomy and trust.

1.1 Motivation for WiFi-Based Beam-Steering

WiFi technology is exceptionally well-suited for beam-steering applications due to its pervasive adoption, robust standardized protocols, and advanced beamforming capabilities embedded in modern standards. The global proliferation of WiFi has created an extensive ecosystem of compatible devices, ranging from consumer electronics to enterprise-grade networking equipment. This widespread use ensures that beam-steering solutions built on WiFi can be deployed across diverse environments, from urban households to large-scale industrial facilities, without requiring proprietary hardware or niche infrastructure. The standardized protocols defined by the IEEE 802.11 family, particularly in newer iterations such as 802.11ac, 802.11ax, and 802.11be, provide a reliable and interoperable framework for implementing beam-steering. These standards incorporate sophisticated beamforming techniques that enable precise control over signal directionality, allowing devices to focus radio energy toward specific receivers. This capability significantly enhances signal strength, reduces interference, and improves data throughput in challenging environments, such as densely populated urban areas or complex indoor settings with multiple obstacles. Moreover, WiFi's ability to dynamically adapt to changing network conditions through channel sensing and adaptive modulation makes it an ideal platform for real-time beam-steering, ensuring optimal performance even in dynamic or congested scenarios.

In comparison to other RF technologies, WiFi-based beam-steering offers compelling advantages in terms of cost-effectiveness, scalability, and compatibility with existing infrastructure. Unlike specialized RF technologies, such as mmWave systems or proprietary wireless protocols, WiFi leverages a mature and widely deployed hardware ecosystem. This reduces the need for costly, custom-built transceivers or antennas, making WiFi-based solutions more affordable for both manufacturers and end-users. The economies of scale driven by WiFi's global adoption further lower component costs, enabling cost-efficient deployment of beam-steering technologies across a wide range of applications. Scalability is another key strength, as WiFi supports seamless integration with an extensive array of devices, from low-power IoT sensors to high-performance access points. This versatility allows WiFi-based beam-steering to cater to diverse use cases, such as smart homes, enterprise networks, and even emerging applications like Vehicle-to-Everything (V2X) communication. Additionally, WiFi's compatibility with existing network infrastructure ensures that beam-steering capabilities can be introduced through software updates or minimal hardware upgrades, avoiding the need for expensive infrastructure overhauls required by other RF technologies. For instance, technologies like mmWave, while offering high bandwidth, demand dedicated high-frequency transceivers and face challenges with signal attenuation, necessitating costly repeaters or base stations. In contrast, WiFi operates in the $2.4\,\mathrm{GHz}$, $5\,\mathrm{GHz}$, and increasingly $6\,\mathrm{GHz}$ bands, which provide a balanced trade-off between range, penetration, and data rates, making it more practical for widespread deployment. Furthermore, WiFi's robust security protocols, such as WPA3, ensure that beam-steering applications can maintain high levels of data integrity and privacy, a critical consideration for sensitive applications like smart cities or healthcare systems. By capitalizing on these strengths, WiFi-based beam-steering emerges as a versatile, cost-effective, and future-proof solution for next-generation wireless connectivity.

2 Background and Related Work

The rapid evolution of wireless communication technologies, particularly WiFi, has transformed how devices connect and interact within diverse environments. Leveraging the widespread adoption of IEEE

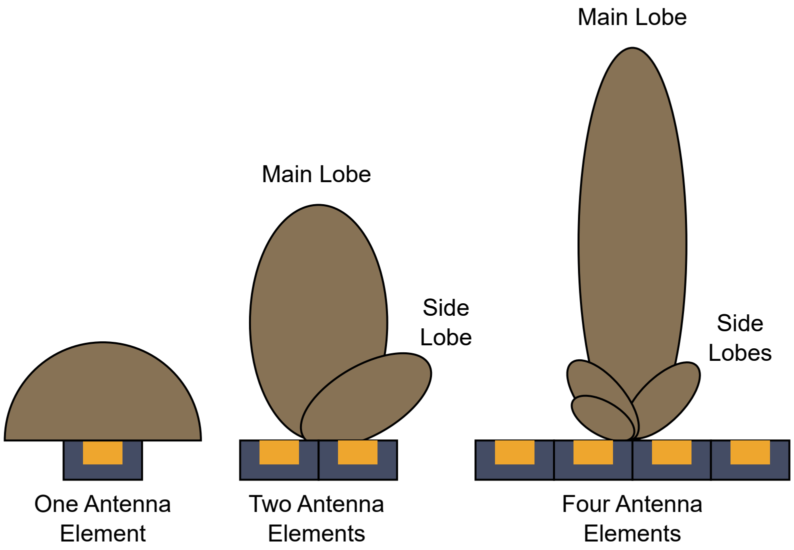

Figure 1: Illustration of radiation patterns with increasing antenna elements, showing the evolution of the main lobe and side lobes from one antenna element to four, highlighting the improved directional focus achieved through beam-steering.

802.11 standards, WiFi has become a cornerstone for modern networking, offering robust, scalable, and cost-effective solutions for both communication and emerging applications like sensing. This section explores the foundational principles of WiFi-based technologies, with a focus on beam-steering and its applications, alongside related work that highlights advancements in RF signal manipulation and environmental sensing, setting the stage for understanding the innovations proposed in this project.

2.1 Wi-Fi Beam-Steering Technology and Its Role in Sensing

Beam-steering is a central technology in advanced wireless communications, including the latest Wi-Fi standards (e.g., IEEE 802.11ax/be). It involves electronically directing the antenna's main radiation lobe towards a specific spatial direction by adjusting the phase of signals at each antenna element in a phased array. This spatial selectivity not only optimizes wireless throughput and reliability but also creates new opportunities for Wi-Fi-based sensing. As illustrated in Figure 1, the use of multiple antenna elements significantly refines the radiation pattern, with the main lobe becoming narrower and side lobes more pronounced as the number of elements increases from one to four, demonstrating the enhanced directional control enabled by beam-steering technology.

Beam-steering leverages phased array antennas, where the direction of the main beam is governed by the relative phase shifts applied to individual elements. For a linear array with element spacing d and wavelength λ, the required phase shift $\Delta\phi$ between adjacent antenna elements to steer the beam to angle θ is:

$$\Delta\phi = \frac{2\pi d}{\lambda}\sin(\theta). \tag{1}$$

The main beam direction θ can then be found as:

$$\theta = \sin^{-1}\left(\frac{\lambda\Delta\phi}{2\pi d}\right), \tag{2}$$

where d is antenna spacing, λ is wavelength of the carrier, $\Delta\phi$ is phase shift between elements, and θ is steering angle.

Altering these phase shifts electronically allows beam steering at speeds much greater than mechanical adjustment, enabling dynamic adaptation to environmental or application changes. Beam-steering technologies greatly enhance Wi-Fi's capability as a sensing platform. By dynamically altering the spatial direction of the transmitted or received beams, smart antennas can probe specific parts of the environment, collecting diverse radio signal measurements. This diversity in spatial views increases sensing robustness and spatial resolution.

A key approach in Wi-Fi sensing is monitoring changes in the Channel State Information (CSI) or feedback matrices when the beam is steered to different directions. For example, advanced Wi-Fi standards transmit Null Data Packets (NDP), and the resulting channel measurements enable the construction of a steering (beamforming) matrix derived from the channel's Singular Value Decomposition (SVD):

$$\mathbf{H}_k = \mathbf{U}_k \Sigma_k \mathbf{V}_k^{\dagger}, \tag{3}$$

where $\mathbf{H}_k$ is the channel matrix on subcarrier k, and $\mathbf{V}_k$ is the unitary steering matrix used for beamforming [43].

With access to steering matrices and the ability to dynamically reorient the main lobe, Wi-Fi devices can detect and classify motion by tracking changes in dominant Angle-of-Arrival (AoA) estimates [32], sense presence, gestures, and even minute breathing patterns in a contactless way. Processing the variation in CSI or beam feedback resulting from environmental changes—such as a person walking through the area swept by the beam—enables rich passive sensing capabilities.

In conclusion, Wi-Fi beam-steering not only boosts communication efficiency but also transforms access points into rich, environment-sensitive sensors—enabling novel joint communication and sensing applications within the scope of next-generation wireless systems.

2.2 RF-Based Sensing: Principles and Evolution

RF sensing leverages the properties of electromagnetic wave propagation and interaction with objects to infer environmental information. The transmitted RF signal propagates through space and undergoes phenomena such as reflection, diffraction, and scattering. The analysis of the received signal enables detection and characterization of objects and their dynamics.

2.2.1 Fundamentals of RF Wave Propagation

Building upon the deliverable D3.6, the transmitted RF signal can be modeled as a time-varying electromagnetic wave:

$$s(t) = A\cos(2\pi f_c t + \phi), \tag{4}$$

where A is the amplitude, f_c is the carrier frequency, and ϕ is the phase.

As the wave propagates, the Free-Space Path Loss (FSPL) determines the received power P_r at a distance d from the transmitter with power P_t:

$$P_r = P_t \left(\frac{\lambda}{4\pi d}\right)^2, \tag{5}$$

where $\lambda = \frac{c}{f_c}$ is the wavelength and c is the speed of light.

When the transmitted wave encounters an object, part of the energy is reflected back. The reflected signal experiences a time delay τ proportional to the distance d to the target:

$$\tau = \frac{2d}{c}. \tag{6}$$

This two-way propagation delay forms the basis of range estimation in RF sensing.

2.2.2 Signal Analysis for Sensing

The received signal $r(t)$ is a superposition of multipath components, including the line-of-sight and reflections:

$$r(t) = \sum_{k=0}^{K} \alpha_k s(t - \tau_k) e^{j2\pi f_{D,k} t} + n(t), \tag{7}$$

where:

- α_k is the complex amplitude of the k^{th} path,
- τ_k is the delay of the k^{th} path,
- $f_{D,k}$ is the Doppler shift due to target motion on the k^{th} path,
- $n(t)$ is additive noise.

Key parameters extracted for sensing include:

- **Time-of-Flight (ToF)**: Delay τ_k estimates target range,
- **Doppler Frequency** $f_{D,k} = \frac{2v_k f_c}{c}$, where v_k is the radial velocity component, estimates target velocity,
- **AoA**: Using antenna arrays, the angle θ of incoming signals can be estimated via spatial correlation or beamforming techniques.

2.2.3 Historical Evolution: From Radar to WiFi-Based Sensing

Traditional radar systems utilize dedicated narrowband or wideband signals to actively probe the environment. Early pulse radars estimated range using the time delay τ, while continuous-wave Doppler radars measured velocity via frequency shifts.

With advances in wireless communication, commercial WiFi signals operating at $2.4\,\mathrm{GHz}$ and $5\,\mathrm{GHz}$ bands have been repurposed for sensing tasks. WiFi-based sensing exploits existing transmissions and their rich multipath signatures without requiring additional hardware. By integrating beam-steering antennas and MIMO configurations, modern WiFi systems enhance spatial resolution and sensing accuracy.

Beam-steering allows focusing transmitted and received energy directionally, improving the estimation of AoA and suppressing interference. The beamforming weight vector $\mathbf{w}$ is applied across an antenna array of N elements to steer the main lobe towards angle θ_0:

$$\mathbf{w} = \frac{1}{\sqrt{N}} \left[1, e^{-j2\pi \frac{d}{\lambda} \sin(\theta_0)}, \ldots, e^{-j2\pi \frac{d}{\lambda}(N-1)\sin(\theta_0)}\right]^T, \tag{8}$$

where d is the inter-element spacing.

The evolution of RF sensing into WiFi-compliant beam-steering systems offers a seamless integration of communication and sensing functionalities, paving the way for intelligent environments and context-aware applications.

2.3 Applications of RF Sensing

RF sensing has emerged as a versatile technology for enabling a wide range of applications, particularly in the domains of gesture recognition [26], motion tracking [30], water content analysis [31], and object detection [47]. Gesture recognition leverages RF signals to interpret human movements, such as hand gestures or body postures, enabling intuitive human-computer interfaces without the need for physical contact or wearable devices. This capability is particularly valuable in environments where touch-based or camera-based systems are impractical, such as in low-light conditions or through occlusions. Motion tracking extends RF sensing to monitor the movement of individuals or groups, offering applications in indoor navigation, crowd monitoring, and activity recognition. Object detection, on the other hand, utilizes RF reflections to identify and locate physical entities, supporting use cases like inventory management and environmental mapping. Real-world deployments of RF sensing have demonstrated significant impact across multiple sectors. In healthcare, RF-based systems monitor vital signs [7], such as heart rate and respiration, without invasive sensors, enhancing patient comfort and enabling remote care. In security, RF sensing facilitates non-intrusive surveillance and anomaly detection [33], improving safety in public spaces. Additionally, automation applications leverage RF sensing for tasks like robotic navigation in warehouses and smart home device control [35], streamlining operations and enhancing user experiences. These deployments highlight the transformative potential of RF sensing, setting the stage for its integration with WiFi-compliant beam-steering technologies in the HOLDEN project.

2.4 WiFi Technology and Beam-Steering

WiFi technology, built on standards like IEEE 802.11ax [4], 802.11be [5], and 802.11ad/ay [3], provides a robust foundation for RF-based sensing due to its widespread adoption and advanced signal processing capabilities. IEEE 802.11ax, also known as WiFi 6, introduces enhanced multi-user MIMO and Orthogonal Frequency-Division Multiple Access (OFDMA), enabling efficient spectrum utilization and precise signal control. IEEE 802.11be, or WiFi 7, further advances these capabilities with wider channel bandwidths and improved modulation, supporting high-resolution sensing applications. The 802.11ad and 802.11ay standards operate in the $60\,\mathrm{GHz}$ millimeter-wave band, offering high data rates and fine spatial resolution, ideal for beam-steering applications. Beam-steering mechanisms, central to these standards, enable directional control of RF signals to focus energy on specific targets. Phased arrays, which adjust the phase of signals across multiple antennas, provide analog beamforming for precise directional control. MIMO systems, utilizing multiple antennas at both the transmitter and receiver, enhance signal robustness and enable spatial multiplexing for simultaneous sensing of multiple targets. Massive MIMO, an evolution of MIMO, employs dense antenna arrays to achieve fine-grained beam control, significantly improving localization accuracy and tracking capabilities. These mechanisms collectively enhance the precision and efficiency of WiFi-based RF sensing, aligning with HOLDEN's goal of ubiquitous perception.

2.4.1 Limitations of Current WiFi Systems

Despite their advancements, current WiFi systems face several technical and ethical challenges that limit their effectiveness for RF-based sensing. Interference, particularly in dense urban environments, degrades signal quality due to overlapping WiFi networks and multipath effects, complicating accurate sensing. Range limitations, especially in the $60\,\mathrm{GHz}$ band used by 802.11ad/ay, restrict sensing capabilities in larger spaces, necessitating advanced beamforming techniques to extend coverage. Computational complexity poses another challenge, as processing high-dimensional RF data for real-time sensing requires significant computational resources, particularly for massive MIMO and holographic processing. Beyond technical constraints, privacy and ethical concerns are critical barriers. Current WiFi sensing solutions often collect detailed spatial and behavioral data without adequate user consent or anonymization, raising risks of unauthorized tracking and data misuse. Ethical issues (illustrated in D4.3), such as the potential for surveillance or profiling, further complicate deployment, particularly in sensitive applications like healthcare and smart homes. Addressing these limitations requires innovative approaches, such as adaptive beamforming to mitigate interference, energy-efficient algorithms to reduce computational demands, and privacy-by-design frameworks to ensure ethical compliance, all of which are central to the HOLDEN project's objectives.

3 WiFi-Compliant Beam-Steering Technology

WiFi-compliant beam-steering technology represents a pivotal enabler for the HOLDEN project's vision of privacy-centric RF-based sensing, offering precise directional control of radio signals within standardized WiFi protocols. By focusing RF energy toward specific targets, beam-steering enhances localization, tracking, and activity recognition, critical for applications in smart living, automated logistics, and free-space interaction. This technology leverages existing WiFi infrastructure, ensuring scalability and cost-effectiveness, while addressing privacy concerns through targeted sensing to minimize unnecessary data capture. This section explores the technical foundations of beam-steering in WiFi systems, its alignment with HOLDEN's privacy-by-design principles, and its implementation across various WiFi standards, with a focus on enabling technologies, hardware requirements, and privacy-centric configurations.

3.1 Enabling Technologies in WiFi Generations

The evolution of WiFi standards has progressively enhanced beam-steering capabilities, driven by advancements in antenna design, signal processing, and spectrum utilization. Standards such as IEEE 802.11ad [2], 802.11ay [3], 802.11ax [4], 802.11be [5], and the emerging 802.11bn (WiFi 8) [1] introduce distinct features that support RF-based sensing for HOLDEN's objectives, including high-resolution localization and multi-target tracking. Figure 2 presents a stacked bar chart comparing these standards across four key beam-steering metrics: frequency band, channel bandwidth, angular resolution, and maximum spatial streams, as shown below.

The chart illustrates significant differences in beam-steering capabilities across WiFi generations. The frequency band metric shows that 802.11ad and 802.11ay operate at $60\,\mathrm{GHz}$, enabling high-resolution beam-steering due to shorter wavelengths, ideal for HOLDEN's Path 1 (continuous-space measurement via holographic processing). In contrast, 802.11ax ($5\,\mathrm{GHz}$), 802.11be, and 802.11bn ($6\,\mathrm{GHz}$) offer broader coverage but coarser resolution, suitable for larger-scale environments. Channel bandwidth highlights 802.11ay's dominance with $8640\,\mathrm{MHz}$, supporting high-data-rate sensing critical for Path 3 (signal processing), while 802.11ad ($2160\,\mathrm{MHz}$), 802.11be/bn ($320\,\mathrm{MHz}$), and 802.11ax ($160\,\mathrm{MHz}$) provide progressively lower bandwidths. Angular resolution, where lower values indicate better precision, positions 802.11ay ($2°$) as the leader, followed by 802.11ad ($5°$), 802.11bn ($8°$), 802.11be ($10°$), and 802.11ax ($15°$), directly impacting the accuracy of localization in Paths 1 and 2. Maximum spatial streams reflect multi-target capabilities, with 802.11be and 802.11bn supporting up to 16 streams, ideal for Path 2 (discrete-space tracking), followed by 802.11ax (8), 802.11ay (4), and 802.11ad (1). Notably, 802.11bn's anticipated enhancements in multi-Access Point (AP) coordination and reliability, as indicated by its improved angular resolution over 802.11be, position it as a promising candidate for future privacy-centric sensing applications in HOLDEN.

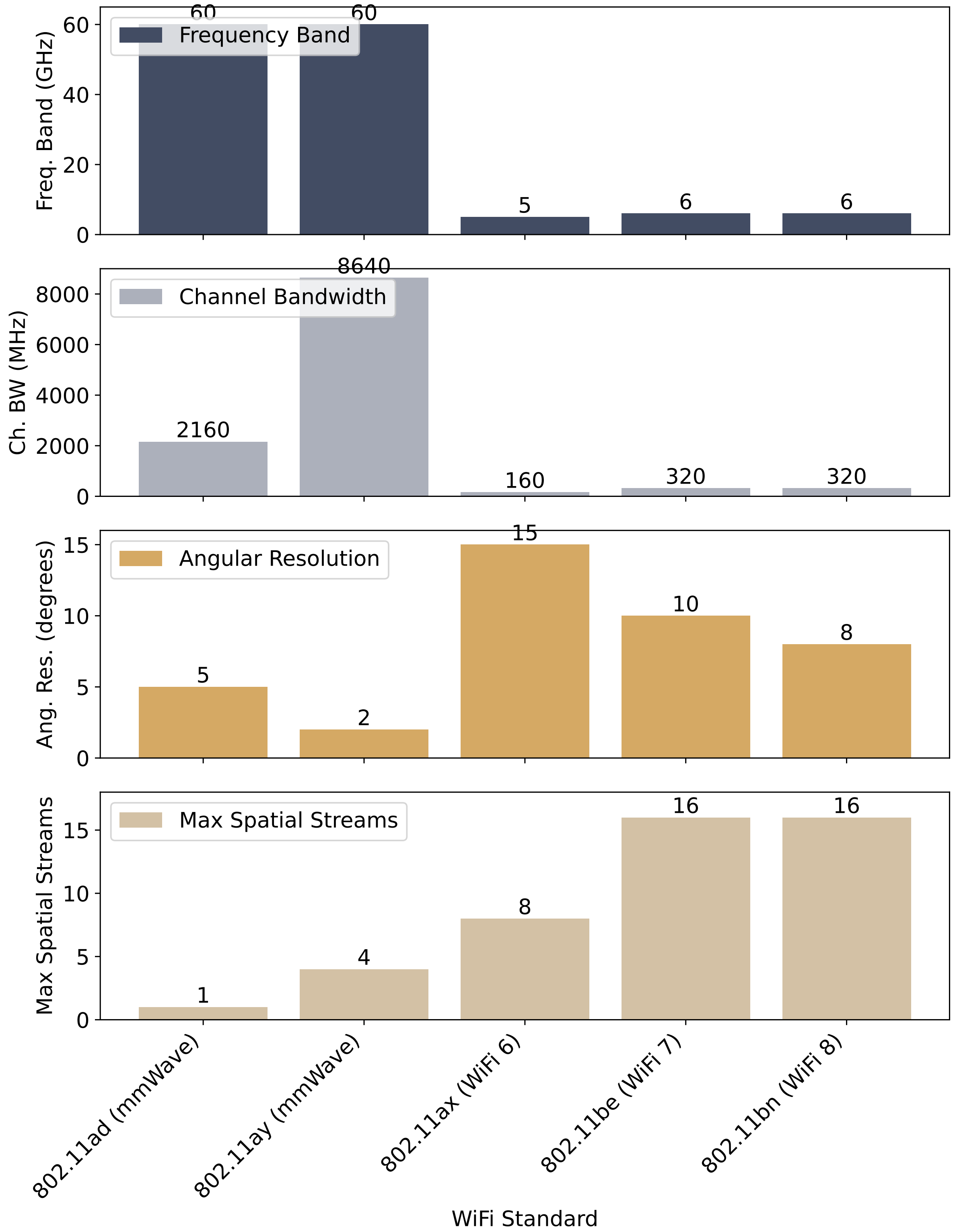

Figure 2: Comparison of WiFi standards (802.11ad, 802.11ay, 802.11ax, 802.11be, 802.11bn) for beam-steering metrics: frequency band, channel bandwidth, angular resolution, and maximum spatial streams.

3.2 Technical Foundations

Beam steering is a fundamental technique employed to maximise the duration and quality of connectivity between wireless devices, such as a moving vehicle and fixed APs [23]. It involves dynamically adjusting the propagation path of a signal to establish a more robust connection with a specific user or group of devices [16]. This process achieves strong directionality, allowing signals to be transmitted primarily in a particularly preferred direction [39]. This focused transmission notably enhances signal strength and reception efficiency, thereby improving overall communication.

At its core, beam steering utilises phased array antennas, which comprise multiple smaller antenna elements arranged in a specific configuration. The mechanism relies on controlling the phase and amplitude of signals emitted from each individual antenna element. By meticulously altering these parameters, the antenna array generates a focused beam through constructive interference in the desired direction, while concurrently suppressing interference from other directions [14]. Accurate estimation of channel parameters, such as channel strength and phase, is crucial for effective beamforming, often leveraging algorithms like Least Mean Square (LMS) methods and training sequences. Conventional beamforming and smart-antenna systems need precise phase alignment and covariance matrix estimation to determine the optimal beamforming design. Other solutions are based on a pattern reconfigurable antenna system designed such that the beam patterns are dynamically altered on each antenna separately [10, 34]. These systems implement digital beamforming while they do not require precise phase alignment simplifying product integration which opens unprecedented opportunities for scaling up RF sensing systems as well as for integration of communication and sensing services. Conventional beamforming and smart-antenna systems need precise phase alignment and covariance matrix estimation to determine the optimal beamforming design. Other solutions, referred to as Pattern Reconfigurable Antenna Systems (PARS), are designed such that the beam patterns are dynamically altered on each antenna separately. These systems do not require precise phase alignment simplifying product integration which opens unprecedented opportunities for scaling up RF sensing systems as well as for integration of communication and sensing services. This intelligent control and directional focusing enable significant improvements in wireless communication, particularly in overcoming high attenuation, increasing data rates, extending range and coverage, and mitigating interference. It is also critical for managing mobility by enabling frequent re-steering to counter link disruptions caused by slight misalignments [27].

Beam steering technology has been integrated into various Wi-Fi standards to meet evolving demands for higher throughput and more reliable connections. The IEEE 802.11ad standard [2], also known as WiGig, was the first to introduce beam steering in the $60\,\mathrm{GHz}$ band, supporting data rates up to $6.7\,\mathrm{Gbit\,s^{-1}}$ [14, 50]. It uses highly directional, electronically steerable beams to mitigate the significant attenuation inherent at these frequencies [40]. Beam training in 802.11ad is conducted through a sector sweep algorithm, which includes a Sector Level Sweep (SLS) to identify optimal sectors and a Beam Refinement Phase (BRP) for fine-tuning antenna configurations [39]. However, this legacy approach can be inefficient, leading to high latency [48], and its low-layer beam-training protocols are vulnerable to attacks like ”beam-stealing” due to a lack of authentication and encryption before a secure channel is established. Building upon its predecessor, the IEEE 802.11ay standard [3] (also in the $60\,\mathrm{GHz}$ band) aims to deliver even faster and longer-range transmissions, targeting at least $20\,\mathrm{Gbit\,s^{-1}}$ throughput, and potentially up to $100\,\mathrm{Gbit\,s^{-1}}$ via multi-stream multiplexing [13, 50]. Key advancements in 802.11ay include channel aggregation, bonding, and advanced MIMO beamforming, supporting concurrent spatial streams from the AP to multiple clients. Its two-layer beam training framework involves initial beam sweeps for single-stream links and a subsequent MIMO training phase, with research focusing on efficient transmit antenna configurations that consider transmit diversity and inter-symbol interference [19].

The evolution continues with IEEE 802.11ax (Wi-Fi 6) [4] and IEEE 802.11be (Wi-Fi 7) [5]. Wi-Fi 6 expands operation to the $2.4\,\mathrm{GHz}$ band alongside $5\,\mathrm{GHz}$, offering wider coverage and enhanced performance, and capable of utilising dual-band beam steering antennas. Despite these advancements, 802.11ax remains susceptible to ”BeamSteal” attacks due to unencrypted beamforming feedback [15]. The forthcoming Wi-Fi 7, or 802.11be, is designed for Extremely High Throughput (EHT), anticipating data rates up to $40\,\mathrm{Gbit\,s^{-1}}$ in sub-$7\,\mathrm{GHz}$ channels [18]. It introduces revolutionary features such as native Multi-Link Operation (MLO), channel sounding optimisation for massive MIMO, and Coordinated Beamforming (CBF). CBF enables multi-antenna APs to multiplex stations more effectively by spatially directing beams while minimising interference [17]. To address the challenge of precise beam alignment in the more complex beam search spaces of Wi-Fi 7 (e.g., 16x16 MIMO), research proposes Ultra-Wide-Band (UWB) assisted localisation to accelerate beam adjustment, leveraging UWB's immunity to multipath effects and precise ToF measurements, further refined by Received Signal Strength Indicator (RSSI) metrics [17].

The implementation of Wi-Fi compliant beam-steering technology relies on specific hardware components, primarily antenna arrays, coupled with intricate phase shifters and sophisticated Digital Signal Processing (DSP) units. These components work in concert to achieve directional signal focusing and control, which is crucial for maximizing connection quality and duration in wireless networks.

At the heart of beam steering are phased array antennas, which comprise multiple smaller antenna elements arranged in a specific configuration. These arrays enable beamforming by dynamically adjusting the propagation path of a signal. For instance, early experimental setups like MobiSteer utilized electronically steerable Phocus Array antennas from Fidelity Comtech for the $2.4\,\mathrm{GHz}$ IEEE 802.11b/g band, which consist of eight elements driven by eight transmit/receive (T/R) boards. Each T/R board acts as a vector modulator, controlling the phase and gain of signals from individual elements to generate various beam patterns. In the $60\,\mathrm{GHz}$ band, where signals are highly vulnerable to attenuation, compacting many miniature antenna elements into a phased-array compensates for path loss; for example, an IEEE 802.11ad 16-element phased array can achieve a $20\,\mathrm{dB}$ link quality gain. Modern commercial devices, such as the TP-Link Talon AD7200 router[1], incorporate Qualcomm's QCA9500 802.11ad Wi-Fi chip with a 32-element electronically steerable phased antenna array. The physical layout of these arrays, which can include patch and dipole antennas, leads to irregular but steerable beam patterns.

Advancements also include Multifunctional Reconfigurable Antennas (MRAs) capable of steering beams in multiple directions, such as nine directions in the 802.11 b/g band, or dual-band MRAs for Wi-Fi 6 ($2.45\,\mathrm{GHz}$ and $5.3\,\mathrm{GHz}$) capable of steering beams in three directions ($0°$, $30°$, and $-30°$). Wideband beamforming antenna arrays, particularly relevant for 802.11ac and $4.9\,\mathrm{GHz}$ bands, are designed with a dual substrate capacitive coupling feed for high gain and wide bandwidth, allowing for flexible configurations (e.g., 1x4, 2x4, 4x4 arrays) to achieve varying gain levels (11.16, 14.59, 17.25 dBi) and broad steering capabilities (±40 ° or even 360 ° coverage).

3.2.1 Phase shifters

Phase shifters are critical components within phased array antennas, precisely controlling the phase of the signal at each antenna element to enable constructive interference in the desired direction. While ideal phase shifters offer continuous control, practical $60\,\mathrm{GHz}$ analog phased arrays often use discrete phase shifters (e.g., 2-bit phase shifters supporting $0, \pi/2, \pi, 3\pi/2$). Despite this discretization, the combined effect of multiple elements allows for a vast number of steerable directions. Protocols like the BRP in IEEE 802.11ad/ay necessitate phased antenna arrays with sub-nanosecond fast switching capabilities for rapid beam adjustments. Emerging solutions in microwave photonics also leverage plasmonic phase modulators for ultra-fast beam steering.

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[1] https://www.tp-link.com/us/home-networking/wifi-router/ad7200/

3.2.2 Digital Signal Processing units

DSP units play a pivotal role in complementing analog beam steering, particularly for implementing advanced beamforming algorithms. In systems like IEEE 802.11n, adaptive beamforming can be performed for each Orthogonal Frequency-Division Multiple (OFDM) subcarrier by dynamically changing complex beamforming matrices in the frequency domain before the Inverse Discrete Fourier Transform (IDFT). For millimeter-wave networks, Base Band Units (BBUs) utilize DSP and high-end electronic front ends to generate signals for multiple users, which are then transmitted over optical fibers to Remote Radio Heads (RRHs). While DSP is powerful, it can be computationally expensive for the high speeds required in millimeter-wave applications. DSP units are also essential for tasks like signal recovery, timing, carrier synchronization, and equalization in receivers. In the context of next-generation Wi-Fi 7 (IEEE 802.11be) [5], channel sounding optimization is a key area of research to reduce the massive overhead associated with exchanging CSI for high-order Multi-User-MIMO and OFDMA in wide channels. This includes efforts towards implicit channel sounding, which relies on uplink/downlink channel reciprocity but requires APs to implement calibration methods to counteract hardware mismatches.

3.2.3 Integration with existing Wi-Fi infrastructure

Integration with existing Wi-Fi infrastructure is a paramount consideration for the widespread adoption of beam-steering technology. To control beam patterns, early systems like MobiSteer [23] interfaced with the wireless card via a serial line command, requiring patched drivers to expose an interface for user-level programs (e.g., through /proc virtual file system in Linux), with subsequent optimizations to reduce beam switching latency. Importantly, some beam-steering systems are designed to operate at the application layer, controlling the RF switch and antenna patterns at the physical layer without modifying intermediate protocol layers, which facilitates retrofitting them into existing non-adaptive communication systems. Current Wi-Fi standards, particularly those operating at millimeter-wave frequencies, have specific frameworks for beam steering:

- **IEEE 802.11ad**: This standard extensively uses predefined beam patterns, known as sectors. The core mechanism for establishing directional links is the SLS algorithm, which exhaustively probes all sectors to find the optimal signal path. An optional BRP further refines the selected sectors and optimizes antenna weight vectors for improved performance. However, the exhaustive nature of SLS can lead to high latency, especially under user mobility, and its low-layer beam-training protocols are vulnerable to beam-stealing [39] attacks due to a lack of authentication and encryption before a secure channel is established.

- **IEEE 802.11ay**: As an enhancement to 802.11ad, this standard aims for faster and longer-range transmissions, targeting multi-gigabit throughputs (e.g., $20\,\mathrm{Gbit\,s^{-1}}$). It introduces a two-layer beam training framework that involves initial beam sweeps for single-stream links and a subsequent MIMO training phase for multi-stream communication. It supports Single-User MIMO and Multi-User MIMO beamforming. The standard also enables the AP to transmit concurrent spatial streams to multiple clients, necessitating multiple RF chains at the AP. Additionally, IEEE 802.11ay discusses cooperation between high-frequency (mmWave) and low-frequency ($2.4\,\mathrm{GHz}$ and $5\,\mathrm{GHz}$) bands, where the lower frequencies can assist the higher ones in beamforming training and tracking, and facilitate Fast Session Transfer (FST) during blockages.

- **IEEE 802.11ax (Wi-Fi 6)**: This standard expands operation to include the $2.4\,\mathrm{GHz}$ band alongside $5\,\mathrm{GHz}$, supporting dual-band beam steering antennas. However, like 802.11ad, 802.11ax remains susceptible to Beam Steal attacks due to unencrypted beamforming feedback.

- **IEEE 802.11be (Wi-Fi 7)**: Designed for EHT, targeting data rates up to $40\,\mathrm{Gbit\,s^{-1}}$, Wi-Fi 7 introduces significant advancements. It supports higher orders of Multi-User MIMO (up to 16 spatial streams) and features like native multi-link operation, optimized channel sounding, and CBF. CBF enables multi-antenna APs to more effectively multiplex stations by spatially directing beams while minimizing interference. To accelerate beam alignment in complex Wi-Fi 7 scenarios (e.g., 16x16 MIMO), research proposes UWB assisted localization [17], leveraging UWB's immunity to multipath effects and precise time-of-flight measurements. This advanced standard aims for backward compatibility with legacy 802.11 devices across $2.4\,\mathrm{GHz}$, $5\,\mathrm{GHz}$, and $6\,\mathrm{GHz}$ bands. It also considers the need for high-capacity, low-latency wired or wireless (e.g., millimeter-wave) backhaul links for multi-AP coordination. Note that this latest standard is selected as reference for benchmark testing in the ADANT testhouse environment (WP6).

3.3 Beam-Steering Techniques

Beam steering is a critical technology for enhancing WiFi performance, particularly in modern Wireless Local Area Networks (WLANs) operating at higher frequencies like $60\,\mathrm{GHz}$ [16, 22]. It involves dynamically adjusting the propagation path of a signal to establish a stronger connection with specific users or devices. This technique leverages phased array antennas, which consist of multiple smaller antenna elements arranged in a particular pattern [16] as discussed in Section 3.2.1. By precisely controlling the phase and amplitude of signals transmitted from each element, the antenna array can create a focused beam through constructive interference in the desired direction, while suppressing interference in other directions. This directional transmission significantly enhances signal strength and reception efficiency for the intended receivers, improving communication efficiency and enabling multi-Gbps connectivity.

Beamforming techniques can be broadly categorised into analog, digital, and hybrid approaches, each with distinct mechanisms, applications, and trade-offs in terms of precision, cost, and computational complexity.

3.3.1 Analog Beamforming

Analog beamforming applies different phase delays to individual antenna elements directly in the RF domain [14]. The steering directions are typically selected from a predefined set of antenna settings, known as a codebook or sectors [39]. For instance, in IEEE 802.11ad, the SLS phase involves exchanging Sector SWeep (SSW) frames across different antenna sectors to identify the one offering the highest signal quality. During a Transmit Sector Sweep (TXSS), frames are sent on various sectors while the receiving node uses a quasi-omnidirectional pattern [24, 39].

It is predominantly used in standards like IEEE 802.11ad, which supports rates up to $6.7\,\mathrm{Gbit\,s^{-1}}$ by transmitting to a single client at a time. MobiSteer, a framework developed for vehicular network access, uses steerable-beam directional antennas in an online mode where it actively probes the environment to choose the best AP and beam combination, or a cached mode which relies on prior radio survey data [23].

While effective at improving Signal-to-Noise Ratio (SNR), analog beam patterns generated by phased arrays can be irregular, sometimes having multiple strong lobes [13]. Some older systems might use mechanically steerable horn antennas to emulate phased arrays, which may not always be representative of the imperfect beams from actual phased arrays. However, the directivity gain in each direction is a known, deterministic function of the codebook and antenna spacing. MobiSteer has demonstrated significant performance advantages, improving throughput by a factor of 2 to 4 in controlled experiments and connectivity duration by more than a factor of 2, with an average SNR improvement of about $15\,\mathrm{dB}$ in in situ experiments [23].

Analog beamforming generally requires a single RF chain per device, making it a lower-cost solution compared to digital beamforming [12]. However, the initial beam training process, such as the exhaustive sequential scanning defined in IEEE 802.11ad, can introduce significant latency, growing quadratically with the number of antenna elements [28]. For example, a 32-antenna phased array can take about $28\,\mathrm{ms}$ to scan [49].

3.3.2 Digital Beamforming

Digital beamforming involves adjusting the signals at the baseband layer using digital weights before they are sent to each antenna element [14]. This allows for more flexible and precise control over the beam shape and direction. Precoding schemes, such as zero-forcing, can be applied to minimise or cancel inter-user interference in multi-user simultaneous transmissions.

It is commonly used in sub-$6\,\mathrm{GHz}$ WLANs. In the context of radar sensing, digital beamforming, specifically Multi-User MIMO precoding, can enhance spatial awareness by directing beams towards targets to improve Signal-to-Interference-and-Noise Ratio (SINR) and suppress static clutter [45]. Digital beamforming offers high precision due to fine-grained control over each antenna element. However, achieving spatial multiplexing gains in $60\,\mathrm{GHz}$ WLANs with digital precoding can be challenging, as receivers may not effectively share an analog beam, sometimes even leading to lower sum capacity than without digital precoding [14].

A significant drawback of digital beamforming is the high cost, as each spatial stream requires an expensive RF chain [12]. This can make full digital beamforming impractical for low-cost user equipment, especially in mm-wave systems [27].

3.3.3 Hybrid Beamforming

Hybrid beamforming combines elements of both analog and digital beamforming. It partitions the signal processing between the RF and digital domains to achieve a performance level similar to fully digital beamforming, but with fewer RF chains [9, 12]. For example, the IEEE 802.11ay standard introduces a two-layer beam training framework: first, an analog beam sweep to find the best single-stream configuration, followed by a MIMO training phase (local search) over a subset of analog beams [13].

This approach is crucial for the next generation of $6\,\mathrm{GHz}$ WLAN standards, such as IEEE 802.11ay, which aims to support concurrent spatial streams from an AP to multiple clients. It is also being explored for 5G cellular networks [12].

Hybrid beamforming seeks to balance flexibility and cost while meeting performance requirements. Algorithms like MUlti-stream beam-Training for mm-wavE networks (MUTE) leverage channel sparsity and knowledge of mm-wave RF codebook beam patterns to select candidate beams that offer diverse or orthogonal paths, achieving up to $90\,\%$ of the maximum achievable aggregate physical layer rate. Experimental results indicate that decoupling beam steering and user selection in a hybrid system can incur less than $5\,\%$ performance loss compared to joint user-beam selection, despite its simplicity and lower complexity [13].

Hybrid beamforming significantly reduces the prohibitive training and feedback overhead associated with joint optimisation of analog beams, user selection, and digital weights. For instance, MUTE incurs only $1.2\,\%$ of the training overhead compared to an exhaustive search [13]. Low-complexity BeamForming Training (BFT) methods for 802.11ay can drastically reduce complexity with negligible loss in MIMO capacity compared to exhaustive search, making Multi-User MIMO more practical [50]. The ”smart beam steering algorithm” for $60\,\mathrm{GHz}$ indoor WLANs under node mobility, which uses knowledge of previous feasible sector pairs, achieves a 7-fold reduction in sector search space on average, directly translating into

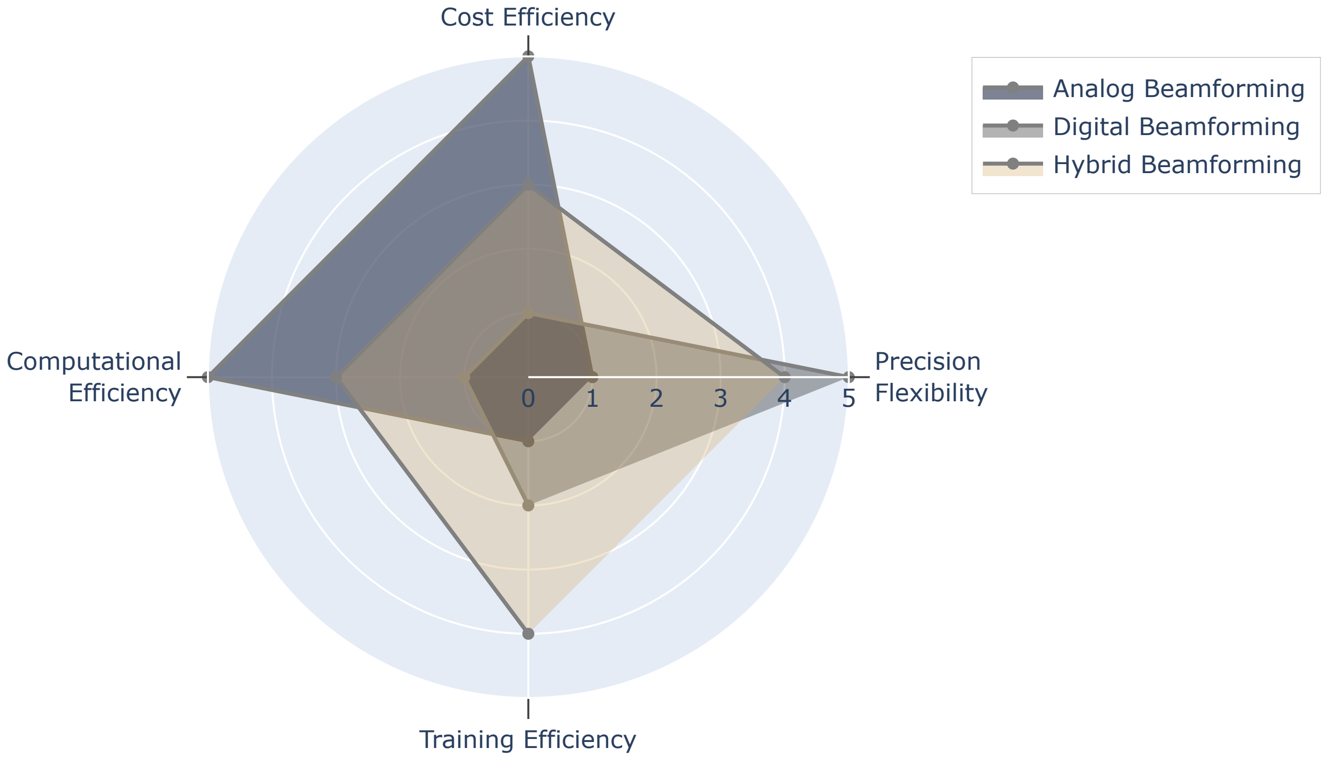

Figure 3: Comparison of analog, digital, and hybrid beamforming architectures across four performance dimensions relevant to WiFi-compliant beam-steering: precision/flexibility, training efficiency, computational efficiency, and cost efficiency.

lower link re-establishment latency without requiring specialty equipment or extra AP-User Equipment (UE) coordination overhead [27].

Fig. 3 presents a radar plot comparing analog, digital, and hybrid beamforming architectures across the dimensions of precision flexibility, training efficiency, computational efficiency, and cost efficiency.

Analog beamforming achieves the highest cost and computational efficiency because it relies on phase shifters with limited hardware and energy overhead. However, its performance in flexibility and training efficiency is restricted, as it cannot provide fine-grained control of multiple beams simultaneously. This makes it suitable for low-power WiFi deployments but less effective in highly dynamic scenarios.

Digital beamforming shows the opposite trend. It provides maximum precision flexibility by enabling independent control of each antenna element and supporting advanced Multi-User MIMO techniques. At the same time, the architecture imposes high cost and computational requirements since every antenna element requires its own RF chain and high-rate converters.

Hybrid beamforming balances the trade-offs by combining features of both analog and digital approaches. It achieves moderate-to-high performance across all metrics, offering improved training efficiency while avoiding the excessive complexity of fully digital systems. For WiFi-compliant beam-steering, this balance makes hybrid beamforming a pragmatic and sustainable design choice, particularly in dense and dynamic environments envisioned within the Holden project.

3.3.4 Performance Comparison in Holographic Scenarios

In this section, we evaluate the performance of the proposed hybrid beamforming approach against a fully digital beamforming upper bound and an isotropic baseline in a multi-target sensing environment, as relevant to WiFi-compliant beam-steering technologies. The simulation setup considers a MIMO system

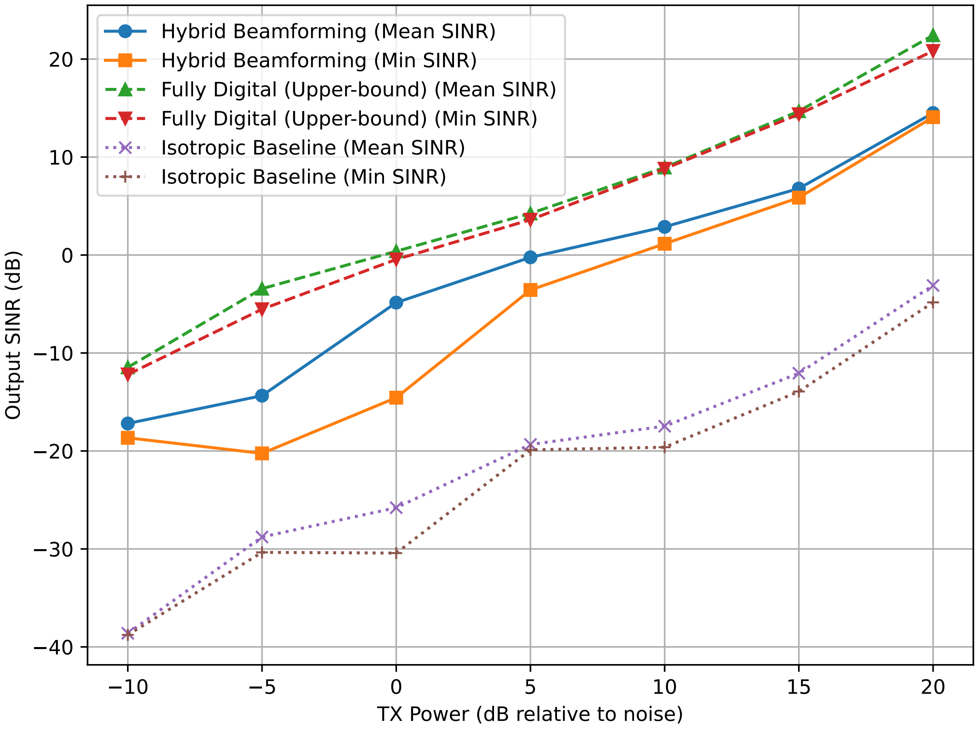

Figure 4: Enter Caption

with 64 transmit antennas and 16 receive antennas, supporting 2 spatial streams corresponding to two targets at angles -10° and 18° with Radar Cross-Sections (RCSs) of 1.0 and 0.6, respectively. Three interferers are present at angles -30°, 5°, and 35° with RCS values of 1.0, 0.8, and 0.9. The sensing channel is modeled as a narrowband monostatic MIMO matrix, incorporating target and interferer contributions with Gaussian-distributed complex amplitudes. Noise variance is set to $\sigma^2 = 1$, and transmit power P varies from $-10\,\mathrm{dB}$ to $20\,\mathrm{dB}$ relative to noise.

The hybrid beamforming design adapts the covariance-fitting algorithm from [36] for the analog precoder under constant-modulus constraints (emulating phase-shifter networks in WiFi hardware), followed by digital-stage normalization via SVD. The receive side employs a similar analog combiner with Minimum Variance Distortionless Response (MVDR) digital combining to suppress interference. In contrast, the fully digital upper bound uses direct SVD of the channel matrix for optimal precoding and combining, assuming full RF chains per antenna for unconstrained flexibility. The isotropic baseline applies uniform power allocation without directional steering, serving as a lower-performance reference.

Figure 4 illustrates the output SINR in dB, showing both mean and minimum values across streams as a function of transmit power. The fully digital approach achieves the highest SINR, benefiting from complete degrees of freedom to maximize signal gain toward targets while nulling interferers, yielding mean SINR values up to approximately $20\,\mathrm{dB}$ at $20\,\mathrm{dB}$ transmit power. This represents the theoretical upper bound for the system, but it requires prohibitive hardware complexity (e.g., 64 RF chains at the transmitter), which is impractical for cost-sensitive WiFi applications.

The hybrid beamforming closely approximates the fully digital performance, with a mean SINR gap of typically $2\,\mathrm{dB}$ to $5\,\mathrm{dB}$ across the power range, narrowing at higher powers where the analog constraints (e.g., phase-only adjustments) become less limiting relative to noise. This is attributed to the effective covariance matching in the analog stage, which promotes energy toward target directions (10° and 18°) while penalizing interferers. The minimum SINR in hybrid mode, reflecting the weaker target (RCS=0.6), remains robust, demonstrating balanced multi-stream support suitable for WiFi beam-steering in dynamic sensing scenarios such as object detection or localization.

In comparison, the isotropic baseline exhibits significantly lower SINR (e.g., mean values $10\,\mathrm{dB}$ to $15\,\mathrm{dB}$ below hybrid at high power), due to the absence of beamforming gain and interference suppression, resulting in diffuse energy distribution. This underscores the advantages of directional beamforming for sensing in interference-prone environments.

Overall, the hybrid design offers a compelling trade-off for WiFi-compliant systems, delivering near-optimal sensing performance with reduced RF chain count, aligning with hardware constraints in emerging WiFi standards like IEEE 802.11ay/be while enabling effective Integrated Sensing And Communication (ISAC) functionalities. Future work may explore quantization effects in phase shifters to further bridge the gap to fully digital bounds.

3.3.5 Privacy-Centric Design

The fundamental characteristics of beam-steering technology, particularly when operating in mm-Wave frequency bands, intrinsically support a robust privacy-centric design by significantly limiting unintended data capture and precisely confining sensing activities to specific regions or targets.

The inherent design of mm-Wave communication systems dictates the use of highly directional, electronically steerable beams to counteract substantial signal attenuation at these higher frequencies [14, 24]. This intrinsic directionality is a cornerstone for privacy, as it naturally concentrates the RF energy within a precisely bounded coverage area, thus reducing the likelihood of signals being received by unintended parties. For instance, algorithms like MobiSteer are specifically engineered to identify and select the optimal AP and beam combination to maximize throughput, which inherently means transmitting signals along a particularly preferred direction to the intended recipient, thereby minimizing energy dispersion into surrounding, unwanted areas [23]. The angular Field of View (FoV) for any sensing applications built upon this technology, such as IEEE 802.11ad-based radar systems, is also directly constrained by the directional analog beam employed, physically limiting the space where data can be captured or sensed [20].

Techniques to further minimize data capture involve optimised beam/sector selection algorithms. These algorithms prevent broad, exploratory signal emissions by precisely targeting the intended communication path. For example, MobiSteer's optimal algorithm for AP and beam selection directly aims to maximise throughput, concentrating signal energy solely on the desired link. Similarly, smart beam steering algorithms for $60\,\mathrm{GHz}$ WLANs significantly reduce the sector search space by drawing upon knowledge of previously effective sector pairs, enabling efficient re-establishment of links to the intended receiver without extensive wide-area scanning.

4 Application Scenarios

In indoor settings, beam-steering drastically extends WiFi range, improves data throughput, and expands coverage in varied environments such as offices, public parks, areas with significant interference, and large conference halls [16]. It is also foundational for applications demanding high-quality video transmissions, including high-definition video conferencing and real-time Miracast, ensuring uninterrupted service even in challenging signal environments [25].

The integration of advanced RF sensing and holographic control over electromagnetic waves is a defining characteristic of these applications. For example, MobiSteer's ability to create an RF signature database through prior radio surveys during idle drives serves as a form of environmental sensing, allowing for optimal AP and beam selection based on learned spatial characteristics [23]. Similarly,

$60\,\mathrm{GHz}$ link profiling, as conducted with platforms like WiMi, enables the monitoring of Received Signal Strength (RSS) at fine resolutions, even without established network associations, and can detect human blockage or device motion [40]. This inherent sensitivity of mmWave links can be proactively exploited for link recovery or diagnosing outages. Technologies like compressive sensing further refine this by enabling efficient beam searching, path tracking, and channel estimation through a minimal number of probes, effectively reconstructing the spatial channel profile [38].

However, as introduced in D4.3, the enhanced capabilities of beam-steering also introduce new privacy and security challenges. The inherent directionality, while beneficial for communication, can create a false sense of security, as underlying beam-training protocols in standards like IEEE 802.11ad often lack robust security mechanisms [39]. This vulnerability can be exploited through beam-stealing attacks, where adversaries inject forged feedback during beam-training to redirect signals towards their location, facilitating eavesdropping or man-in-the-middle attacks. To address this, privacy-centric designs are imperative, particularly the implementation of authenticated beam-training protocols such as the Sector Sweep with Authentication (SSA) [37]. SSA ensures that devices only accept beam-training responses from legitimate and intended peers, thereby preventing unauthorised manipulation of beam selection and signal misdirection. Future security solutions may also incorporate physical layer security methods that leverage the inherent randomness of wireless channels and other physical aspects of propagation [15].

4.1 Logistics

In the logistics sector, WiFi-compliant beam-steering technology offers transformative potential for automated inventory tracking and optimised warehouse navigation [42]. In a smart warehouse, beam-steering antennas can significantly improve localisation accuracy for positioning systems, which is critical for precise tracking of goods and guiding Autonomous Guided Vehicles (AGVs). By using narrow beamwidths, these systems can minimise the effects of multipath signals, leading to more accurate location estimations even with fewer antenna elements [42].

Supply chain monitoring greatly benefits from beam-steering by ensuring enhanced and continuous connectivity, enabling the collection of real-time data from mobile assets. Vehicles can function as mobile sensors, utilising frameworks like MobiSteer to upload diverse information on driving conditions, road status, traffic, and environmental factors to a centralised database. This real-time data facilitates dynamic adjustments in supply chain operations, as it can be accessed by other vehicles or monitoring applications. The robust and persistent connectivity provided by steerable beams, even in challenging mobile scenarios, is essential for maintaining efficient logistics operations [23].

The holographic and sensing aspects of RF are central to these applications. Advanced beam-steering mechanisms can leverage environmental sensing to dynamically adapt and maintain optimal communication links. MobiSteer, for example, employs a cached mode that constructs an RF signature database from prior radio surveys during idle periods. This database, rich in location, timestamp, AP, channel, datarate, beam, and SNR information, then guides an optimal beam steering and AP selection algorithm when a vehicle is on a familiar route, effectively using stored spatial knowledge to enhance connectivity. For unfamiliar routes, an online mode actively probes all beams and channels to collect real-time SNR values, enabling on-the-fly selection of the best AP and beam combination. Similarly, smart beam-steering algorithms for mmWave WLANs leverage historical data of feasible sector pairs to reduce the search space for re-establishing links following node mobility. This remembered spatial awareness significantly reduces latency and improves link re-establishment efficiency, which is vital for mobile assets in dynamic logistics environments.

4.2 Smart Living

In the context of smart living, WiFi-compliant beam-steering technology facilitates a new generation of home automation and health monitoring applications, significantly improving user experience through personalised and responsive environments. For example, in smart homes, beam-steering antennas can efficiently connect scattered smart devices to a central control hub, ensuring stable and high-quality communication for seamless automation [29].

RF sensing, a fundamental holographic aspect, enables advanced monitoring capabilities without requiring invasive sensors. By accurately detecting AoA from CSI, as demonstrated by the SpotFi algorithm, beam-steering antennas can precisely locate connected devices, including wearable health monitors, or implicitly detect human presence and movement [42]. This capability supports non-invasive health monitoring functionalities, such as tracking sleep patterns, fall detection, or monitoring activity levels, simply by observing changes in the RF environment [12]. The inherent sensitivity of $60\,\mathrm{GHz}$ links to human blockage and device motion can be proactively exploited to manage link quality or even diagnose link outages, effectively transforming environmental dynamics into actionable data. This system could even potentially discern human gestures or fine-grained movements [12, 40].

Personalised user experiences are significantly enhanced through this advanced RF sensing. For example, a system could adapt lighting or climate control based on a user's presence, occupancy and movement within a room, identified via beam-steering-enhanced localisation [46]. Multimedia content could follow users as they navigate a space, maintaining optimal streaming quality through continuous beam alignment. The concept of beam-forecast further refines this by reconstructing the channel profile at nearby locations without explicit scanning, predicting optimal beams for mobile users with minimal overhead. This model-driven approach, exploiting correlations in $60\,\mathrm{GHz}$ channel profiles, ensures sustained high performance for mobile links [49].

Privacy is a paramount consideration in smart living environments. While RF sensing offers tremendous benefits, the ability to track individuals' movements and infer activities raises significant privacy concerns. Explicit consent and clear transparency about data collection are essential. Designs should prioritise on-device processing of sensitive data, transmitting only anonymised aggregate information to the cloud, or retaining raw data locally with robust access controls. Mechanisms such as SSA are crucial to prevent external adversaries from eavesdropping on home network traffic or manipulating smart devices [37]. Furthermore, research into physical layer security solutions that leverage the randomness of channels could provide robust defences against sophisticated attacks on sensing data [15]. The use of programmable metasurfaces (HyperSurfaces) for intelligent beam steering could also offer privacy benefits by precisely shaping the electromagnetic environment, directing signals only where intended and suppressing leakage into unintended areas, effectively creating private RF zones within a home [8].

4.3 Free-Space Interaction

Free-space interaction applications, including gesture-based control and Augmented Reality (AR) interfaces, are profoundly transformed by WiFi-compliant beam-steering and advanced RF sensing. These technologies enable intuitive, touchless control and highly immersive experiences by accurately tracking user movements and gestures in three-dimensional (3D) space [44, 48].

The core of this capability relies on the highly directional nature of mmWave beams and sophisticated RF sensing techniques. For applications such as wireless AR and Miracast, accurate 3D beam-steering is crucial because even slight user motion or orientation changes can lead to severe link outages. Traditional 2D beam-steering solutions are often insufficient in these dynamic 3D scenarios due to the exponential growth of beam searching complexity [44]. Novel mechanisms like Orthogonal Scanner (OScan) or Parallel Scanner (PSCAN) address this by leveraging a hidden interaction between 3D beams and the spatial channel profile of $60\,\mathrm{GHz}$ radios [48]. These model-driven approaches strategically scan 3D space, significantly reducing search latency and maintaining high throughput, which is vital for the low-latency demands of gesture control and AR.

RF sensing capabilities extend beyond basic localisation to fine-grained motion detection. Research explicitly highlights the potential for Wi-Fi sensing for low-cost, low-complexity hand gesture recognition and high-precision motion detection. This allows users to control devices or interact with AR interfaces using natural hand movements in the air, eliminating the need for physical contact or dedicated wearables. The sensitivity of $60\,\mathrm{GHz}$ links to subtle environmental changes, including human movement, provides a rich source of data for these applications [40].

From a user experience perspective, the responsiveness and accuracy of gesture recognition, driven by agile beam-steering, create a seamless and engaging interaction. The ability to track and adapt to a user's movements in real-time, even with complex 3D rotations, ensures that AR content remains stable and interactive, and gesture commands are reliably interpreted [48].

Privacy and security considerations are equally paramount. As with smart living, the capability for high-precision motion tracking raises concerns about constant surveillance. Designing privacy-preserving gesture interfaces would involve local processing of gesture data, converting raw RF signatures into commands without storing identifiable movement patterns. If any biometric-like data is collected, for example, for user authentication via unique gesture patterns, it must be handled with the highest level of encryption and access control. The threat of beam-stealing attacks remains relevant, where an attacker could remotely manipulate beam steering, potentially intercepting sensitive interaction data or even spoofing gesture commands to control devices maliciously [39]. Implementing robust authentication for SSA and exploring physical layer security solutions that utilise channel randomness are vital safeguards. The use of programmable metasurfaces can further enhance security and privacy in free-space interaction by creating dynamic, localised interaction zones, ensuring that gesture commands or AR data are confined to the intended user and space, thereby minimising unintended signal leakage and eavesdropping opportunities [8].

5 Technical Challenges and Solutions

WiFi-based beam-steering for sensing applications faces several key challenges that must be addressed to ensure robust and privacy-centric operation. Millimetre-wave technology, while offering multi-Gbps throughput, is inherently vulnerable to attenuation, particularly from human blockage and device mobility [40]. Unlike traditional omni-directional antennas, highly directional links, which compensate for significant path loss, introduce new complexities related to these environmental dynamics [50]. Maintaining continuous connectivity, especially with node mobility, necessitates frequent beam re-steering, a process that can lead to excessive delays and disrupt communication if not managed efficiently. Conventional exhaustive sequential scanning approaches, used to identify optimal sector pairs, are time-consuming and scale quadratically with the phased-array size, imposing prohibitive training overhead in mobile scenarios [27].

Furthermore, the opaque firmware and limited interfaces of many off-the-shelf mmWave devices hinder researchers from directly manipulating physical (PHY) and Media Access Control (MAC) layer parameters, making advanced customisations challenging [38]. In multi-link configurations, imperfect beam patterns can also lead to spatial reuse issues [40]. For Wi-Fi 6 applications, connecting numerous scattered smart devices requires routers with efficient scanning beams to maintain stable connections [29]. In broader mmWave deployments, additional challenges arise from free-space propagation losses, non-stationary outdoor environments, and atmospheric effects, all necessitating increased antenna gain and beam steering capabilities [22]. Addressing these challenges, particularly in sensing contexts, requires solutions that are not only technically proficient but also aligned with HOLDEN's privacy-centric goals, ensuring that sensing capabilities do not compromise user privacy through inadvertent data collection or unauthorised access. This involves integrating privacy-by-design principles into the development of beam-steering protocols and hardware.

5.1 Interference and Multipath Effects

In complex environments such as urban areas, WiFi and mmWave beam-steering systems contend with significant interference and multipath effects. Millimetre-wave links are highly susceptible to signal attenuation, which scales unfavourably with carrier wavelength (e.g., $60\,\mathrm{GHz}$ is $21.6\,\mathrm{dB}$ worse than $5\,\mathrm{GHz}$ and $28\,\mathrm{dB}$ worse than $2.4\,\mathrm{GHz}$ in terms of free-space path loss) [40]. Human blockage and device mobility present primary obstacles, necessitating constant adaptation of beam paths. Outdoor mmWave deployments must also account for complex nonstationary environments, mobility, and atmospheric phenomena [22]. The inherent sparsity of mmWave channels means that only a few dominant Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) paths characterise the link between nodes [13, 19]. Beams covering the same physical paths can lead to highly correlated channels, hindering multiplexing gains and causing inter-stream interference. Moreover, traditional omni-directional antennas contribute to mutual interference between adjacent cells and in densely populated areas, degrading signal quality and data rates [41].

To counter these effects, adaptive beamforming and interference cancellation techniques are crucial. Highly directional electronically-steerable beams are employed to compensate for path loss, leveraging directivity gains that scale as $1/\lambda^2$ [40]. Adaptive beamforming dynamically adjusts signal phase and amplitude in real-time, enabling beams to be steered towards target clients while nullifying interference from other directions [41]. Technologies like MobiSteer enhance connectivity and PHY-layer data rates through improved SNR provisioning [23]. The Beam-forecast approach, a model-driven beam steering method, reconstructs channel profiles during device motion to predict and realign optimal beams with minimal overhead, leveraging the high correlation of $60\,\mathrm{GHz}$ channel profiles at nearby locations [49]. Compressive sensing techniques allow for efficient sector selection by probing only a subset of available sectors and inferring the best path from spatial similarities [38]. For multi-user scenarios, zero-forcing precoding schemes can minimise or cancel inter-user interference. However, this is most effective when analog beams are well-chosen to maximise stream separability; otherwise, digital precoding offers limited benefit. Reconfigurable Intelligent Surfaces (RISs) or HyperSurfaces offer a promising solution to blockage, providing programmable reflection to establish reliable channels even in the absence of a LOS path [8]. Techniques such as Extremum Seeking Control (ESC) can autonomously reconfigure HyperSurfaces states to maximise received power. Other solutions include adaptive beam maintenance to adjust data rates and beamwidths, proactive path quality prediction to pre-empt disconnections [38], AoA estimation using $2.4\,\mathrm{GHz}$ signals to predict $60\,\mathrm{GHz}$ sectors and reduce latency [28], and UWB assisted localisation for rapid, multipath-immune beam adjustment [17].

5.2 Privacy and Security

The highly directional nature of beam-steering in WiFi networks, particularly in IEEE 802.11ad, introduces significant privacy and security risks, including data interception and unauthorised sensing. A notable vulnerability is the beam-stealing attack, where attackers inject forged feedback into the unprotected sector sweep protocol, forcing victim devices to steer their beams towards the attacker's location [39]. This significantly boosts the attacker's eavesdropping capabilities and facilitates man-in-the-middle attacks, even with advanced higher-layer encryption like WPA2. Since beam-training protocols occur before a secure channel is established, they remain vulnerable to such low-layer manipulation.

Even with encrypted data frames, attackers can exploit unprotected signalling and channel control to misdirect beams, potentially causing denial-of-service or isolating nodes. Similar physical-layer spoofing vulnerabilities have been identified in Wi-Fi 6's Beamforming Feedback (BFF), where the lack of encryption allows an attacker to impersonate a legitimate user and redirect beams for information theft [15].

To mitigate these threats and align with HOLDEN's privacy-centric goals, robust encryption and anonymisation strategies are essential. The SSA protocol is a proposed solution that extends the standard sector sweep by incorporating authentication mechanisms [37]. By embedding authenticators and nonces into training feedback frames, SSA ensures that devices only accept beam selection feedback from their intended, authenticated peers, preventing attackers from forging these crucial messages. This provides authenticity and integrity protection for the beam-training process. While authenticating sector sweep frames introduces a small overhead, SSA has been shown to incur only about $7.3\,\%$ higher overhead compared to the original sector sweep [39]. Beyond authentication, physical-layer security solutions are needed, potentially leveraging the inherent randomness of wireless channels and other physical propagation characteristics to make attacks more difficult [15]. For sensing applications, a privacy-centric approach would necessitate anonymisation of collected sensing data, strict access control mechanisms, and design choices that prevent the easy inference or direct storage of sensitive personal information, such as precise location or activity patterns, without explicit user consent. Distance bounding and secure device localisation based on mmWave signal characteristics also show promise in detecting and defending against beam-stealing attacks by verifying the physical proximity of communicating devices [39].

5.3 Scalability and Energy Efficiency

Large-scale deployments of beam-steering WiFi systems face significant scalability and energy efficiency challenges. A primary concern is the prohibitive overhead associated with beam training, as exhaustive search methods increase exponentially with the number of stations and the size of the antenna codebook, especially for Multi-User MIMO operations [49]. This extensive search space necessitates that transmitting and receiving antenna weight vectors are determined for multiple simultaneous spatial streams, increasing complexity with each additional stream and higher beam resolution [13]. Conventional omnidirectional antenna deployments demand more APs due to smaller cell radii, leading to higher deployment and maintenance costs [41]. Furthermore, mmWave communications inherently incur significant power consumption due to the large number of antenna arrays required to form directional beams [50]. Existing power management mechanisms, such as those in IEEE 802.11ad, are often inefficient, compelling stations to remain in active mode for entire or continuously await acknowledgments in Multi-User MIMO transmissions, wasting considerable energy [50].

To address these issues, energy-efficient algorithms and hardware designs are critical. Smart beam steering algorithms can drastically reduce the search space and associated latency; some approaches have demonstrated a 7-fold reduction on average and a 3-fold reduction in the worst-case compared to exhaustive searches [27]. The compressive sector selection protocol can speed up sector selection by a factor of 2.3 by only probing a subset of available sectors [38]. Similarly, the FastLink protocol employs compressive sensing to identify dominant channel clusters with $90\,\%$ less search time than 802.11ad scanning methods. MUTE efficiently reuses initial beam acquisition sweeps to estimate beam-specific Power Delay Profiles (PDP) without incurring additional overhead. By selecting candidate beams that capture diverse or orthogonal paths, MUTE achieves nearly $90\,\%$ of the maximum aggregate PHY rate with only $1.2\,\%$ of the training overhead of an exhaustive search [13]. Programmable metasurfaces offer an energy-efficient hardware solution by optimising signal reflection passively, thereby avoiding the active transmission overhead required for traditional beam training [8]. Furthermore, efficient power saving mechanisms are being developed within standards like IEEE 802.11ay, which offers better power management than 802.11ad by allowing stations to transition to sleep mode more quickly and intelligently [50]. Ultimately, the seamless integration of beam steering with existing WiFi standards is paramount for widespread adoption and compatibility [16]. Innovations like Time-to-Space Division Multiplexing (TSDM) are also being explored, utilising ultra-fast beam steering to generate multiple beams with reduced hardware complexity, thereby increasing capacity without burdening user equipment [11].

In summary, addressing the technical challenges of WiFi-based beam-steering for sensing requires a holistic approach that balances performance, scalability, and privacy. While adaptive beamforming, compressive sensing, programmable metasurfaces, and advanced authentication protocols offer promising solutions, their effectiveness ultimately depends on seamless integration into real-world deployments where mobility, interference, and user privacy must be managed simultaneously. Future research should therefore prioritise cross-layer optimisation—bridging PHY/MAC design with higher-layer security and privacy frameworks—while also considering energy efficiency and interoperability with emerging WiFi standards. By aligning these solutions with HOLDEN's vision of privacy-by-design, beam-steering can evolve into a robust and secure enabler of next-generation wireless sensing and communication systems.

6 Future Directions and Research Gaps

Building on the foundational advancements of beam steering in millimeter-wave and advanced Wi-Fi, the future trajectory of this technology is defined by ongoing efforts to overcome inherent challenges and unlock even greater potential. While obstacles like dynamic environmental blockages and high number of users moving concurrently remain prominent concerns, particularly for high mobility environments and dense indoor settings [40], significant progress is being made through smarter algorithms and novel architectural designs. Beam training overhead remains a substantial challenge, as traditional exhaustive sequential scanning and even two-stage hierarchical searches can introduce excessive delays that linearly scale with the number of narrow beams, severely impacting link re-establishment, especially in mobile scenarios or for multi-stream directional links [27]. Furthermore, the complexity of multi-AP coordination and efficient resource allocation in flexible OFDMA and multi-Resource Unit (RU) systems presents ongoing research areas [18]. The critical need for robust security against vulnerabilities like beam-stealing attacks, which exploit the lack of authentication in low-layer protocols, also represents a significant gap [39].

Interdisciplinary approaches are essential to advance these goals, leveraging areas such as UWB-assisted localization for rapid and precise beam adjustment [17], AI and Machine Learning (ML) for optimizing parameters, channel modeling, and adaptive resource allocation [12], and the integration of contextual information and sensor fusion to inform beam alignment [27]. Developing secure low-layer protocols and addressing the practical limitations of current hardware and firmware interfaces are also paramount [38]. Future work will also extend to exploring CBF with multiple access points and enhancing beam alignment with deep learning [17].

6.1 Technical Advancements

Emerging Wi-Fi standards and technologies are poised to introduce sophisticated sensing capabilities and further integrate artificial intelligence with millimeter-wave communications. While specific details on the 802.11bf standard are not available in the provided sources, there is significant discussion on general Wi-Fi sensing. This includes the potential for low-cost and low-complexity Wi-Fi sensing applications such as hand gesture recognition, high-precision motion detection, health monitoring, ranging, and positioning, which are expected to be incorporated into the IEEE 802.11 protocol [12]. Furthermore, MIMO radar capabilities are being integrated into WLAN sensing by leveraging existing protocols and enhancing spatial awareness through Multi-User MIMO precoding for beam steering [45]. Research has also explored the impact of Multi-User MIMO on passive Wi-Fi sensing and AoA estimation using 802.11ax Multi-User MIMO signals [45].

Millimeter-wave technology continues to be a cornerstone for next-generation wireless systems, enabling multi-Gbps data rates essential for 5G-and-beyond mobile networks, vehicular communication, and joint communication-radar systems as seen in IEEE 802.11ad and 802.11ay [40]. The inherent vulnerability of mmWave links to attenuation is effectively compensated by highly directional phased-array antennas. Coupled with this, AI-driven adaptive sensing is emerging as a powerful enabler. ML is considered a promising tool for various aspects of future WLANs, including optimisation of parameters, protocol version selection, multi-channel/multi-link aggregation, channel modeling, fast time-varying channel estimation, modulation recognition, RU allocation, multi-antenna selection for Single-User MIMO/Multi-User MIMO, and multi-AP selection and deployment [12]. Deep learning is specifically applied for mmwave large-scale channel fading prediction [6] and has been investigated for optimising throughput performance in distributed MIMO Wi-Fi networks [18], as well as assisting beam alignment in mmWave systems [17]. Technologies like ESC are employed for feedback-based autonomous reconfiguration of programmable metasurface states to guide impinging waves, demonstrating effectiveness in dynamic environments such as vehicular or Unmanned Aerial Vehicle (UAV) settings [8]. Additionally, model-driven beam steering approaches like Beam-forecast leverage channel correlations to reconstruct channel profiles and predict optimal beams for mobile users with minimal overhead [49].

6.2 Ethical and Policy Research

The widespread adoption of advanced RF sensing and beam steering technologies necessitates a proactive approach to ethical and policy considerations, particularly concerning privacy and security. The sources highlight significant security vulnerabilities, such as beam-stealing attacks, where an attacker can intercept sector sweep protocols and manipulate devices to direct their signals towards the attacker's location, facilitating eavesdropping or man-in-the-middle attacks [39]. This threat is exacerbated by the fact that these attacks occur at low-layers, before a secure link can be established, and standard control frames typically lack authentication mechanisms. The absence of encryption for BFF in Wi-Fi 6 also renders it vulnerable to spoofing attacks [15].

To address these critical issues, there is an urgent need to propose global standards for privacy and ethics-by-design in RF sensing. Solutions such as SSA have been proposed to protect beam-training against forged feedback by authenticating responses from legitimate devices, demonstrating feasibility with minimal overhead [37]. The community must develop proper protection mechanisms for upcoming wireless communication standards, including IEEE 802.11ay and 5G NR, by incorporating authentication and integrity protection at the foundational protocol layers. This is crucial to safeguard against remote manipulation of beam-steering and potential denial-of-service attacks, which carry significant ethical implications.

Furthermore, interdisciplinary collaboration with ethicists and policymakers is indispensable. The complex issue of coexistence among heterogeneous networks, potentially from different vendors and owners, operating in shared unlicensed spectrum (e.g., Wi-Fi with 5G NR-U in the $6\,\mathrm{GHz}$ band), demands tight synchronisation and agreement on regulatory frameworks [18]. This requires collaboration among regulatory bodies (e.g., FCC), standardisation organisations (e.g., IEEE, 3GPP), and industry stakeholders to develop efficient coexistence solutions [21]. The call for chip manufacturers to open their interfaces to allow researchers better low-level access to hardware for evaluating new protocols also underscores the need for industry-academia collaboration to accelerate the development of secure and efficient systems [38]. Academic research plays a vital role in evaluating and developing proposed ideas, highlighting open issues that require joint attention from industry and policy circles.

7 Conclusion

This deliverable has provided a comprehensive analysis of WiFi-compliant beam-steering technology as a pivotal enabler for privacy-centric RF-based sensing within the HOLDEN project's mission to advance ethical ubiquitous perception. It also effectively serves as a reference for the testing activities carried out in the ADANT testhouse. The key findings highlight the promising transformative potential of different beam-steering technologies, supported by advanced WiFi standards such as IEEE 802.11ax, 802.11ad/ay, and the emerging 802.11be/bn, in achieving precise localization, robust multi-target tracking, and sophisticated activity recognition. These capabilities are critical for applications spanning smart living, automated logistics, and free-space gesture interaction, leveraging the widespread adoption of WiFi infrastructure to ensure scalability, cost-effectiveness, and seamless integration into existing networks. The survey has demonstrated how technical innovations, including hybrid beamforming, reconfigurable antenna systems, beam-switching, compressive sensing, and programmable metasurfaces, address challenges such as interference, computational complexity, and mobility, while enhancing sensing accuracy and efficiency.

HOLDEN's contributions extend beyond technical advancements, emphasizing the integration of ethical frameworks and privacy-by-design principles to mitigate risks associated with RF sensing, such as beam-stealing vulnerabilities and unintended data capture. Solutions like secure SSA, localized signal focusing, and on-device data processing ensure compliance with regulatory frameworks like GDPR and ethical AI principles, safeguarding user privacy and trust. By aligning technical solutions with HOLDEN's three complementary paths—continuous-space holographic processing, discrete-space beamforming, and high-dimensional tensor processing—this work establishes a robust foundation for developing privacy-compliant sensing systems that balance functionality with user protection.

The impact of this survey lies in its role as a guiding resource for future research, development and testing in privacy-centric RF sensing. It identifies critical research gaps, including the need for energy-efficient beam training, robust security protocols, and multi-AP coordination, while proposing interdisciplinary approaches that incorporate AI, ML, and UWB-assisted localization. The survey underscores the necessity of collaboration among academia, industry, and policymakers to address these challenges and standardize privacy-preserving protocols for next-generation WiFi standards. This collaborative effort is essential to realize HOLDEN's vision of ubiquitous perception that empowers users in smart environments while prioritizing their autonomy, security, and trust. Moving forward, stakeholders are encouraged to invest in open hardware interfaces, cross-layer optimization, and global standards for ethical RF sensing, ensuring that beam-steering technologies evolve into secure, scalable, and socially responsible solutions for a connected world.

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