REINDEER

D1.3

Assessment of achievable gains in actual deployment scenarios

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Abstract:	This deliverable reports on the results of Task 1.3, complementing the inventory of use cases and technical requirements for KPIs in D1.1, discussing the actual achievable performance based on the results of the project. The results are used to connect the corresponding use cases and KPIs by discussing the essential application requirements, for example energy neutral device (END) operation, positioning, low latency, synchronization or multiple access.
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Executive Summary

This document provides a comprehensive summary of the key requirements for cell-free communication systems, like the RadioWeaves (RW) infrastructure, addressing both the challenges and technical considerations associated with achieving efficient and effective network operation.

The general purpose of this document is to link the research results gained throughout the REINDEER project to the relevant use cases and their requirements defined in Deliverable [D1.1] at the beginning of the project, ensuring that theoretical findings are contextualized within the practical applications in focus. Furthermore, it highlights all the key findings, subdivided according to the key performance indicators (KPIs) for each use case. The outlined topics focus on diverse aspects critical to supporting a wide range of applications and services in this advanced network environment. Each section dives into a specific requirement, offering insights into its significance and the implications for the RW system design and deployment.

Positioning Requirements: Discusses the precision and accuracy needed for location-based services and how these requirements impact network architecture and design. Fundamental performance limits are analyzed theoretically and realized accuracy is evaluated on realistic data acquired with various testbeds.

Energy-Neutral Operation of Devices: Examines strategies for achieving sustainable energy use, emphasizing self-powered or energy-harvesting technologies. Our high-level summary of results draws on detailed research into initial access, near field beamforming in light of regulatory compliance, the impact of synchronization, backscatter communication, and experimental feasibility studies.

Initial Access Supporting Many Devices: Explores mechanisms to efficiently handle initial access and connection establishment in environments with a high density of devices. We demonstrated the performances of our portfolio of initial access schemes theoretically and through simulations and experiments, where some are found effective for connecting to a few devices with high efficiencies and others for moderate efficiencies connecting to massive numbers of devices.

Peak Data Rate Requirements and Aggregate Data Rate: Analyzes the demand for high data throughput and the aggregate capacity necessary to meet user and application needs.

Low Latency and Reliability Requirements: Highlights the criticality of minimizing delays and ensuring reliable communication, particularly for mission-critical applications.

Synchronization Requirements: Details the importance of precise synchronization in enabling coordinated operation across network components with spatially separated clocks. We present algorithms and performance bounds for joint over-the-air (OTA) positioning and synchronization of distributed arrays, reciprocity- or full calibration of distributed arrays, as well as the performance impact of imperfect synchronization.

Multiple Access: Evaluates techniques for facilitating simultaneous access by multiple users or devices, ensuring fairness and efficiency.

Backhaul/Fronthaul Requirements: Investigates the connectivity needs between core networks and distributed components, focusing on bandwidth, latency, and reliability.

Device Mobility: Addresses the challenges associated with maintaining seamless connectivity and performance as devices move within and across network regions. We present both data-driven and model-based approaches to predict future channel state information (CSI) to mobile devices where outdated CSI can no longer fulfill the performance requirements of the defined use cases.

Through detailed discussions of these requirements, this document aims to provide a foundation for understanding the demands of next-generation communication systems and guiding their implementation.

By bridging research outcomes with the requirements from various use case scenarios, the document not only highlights achievements and research contributions, but also identifies limitations, laying the groundwork for future research in this field.

Contents

Glossary

3D three-dimensional.

5G fifth-generation.

AMP approximate message passing.

AP access point.

AR augmented reality.

BER bit error rate.

BH backhaul.

CLK clock.

CPU central-processing unit.

CRLB Cramér-Rao lower bound.

CSI channel state information.

CSP contact service point.

D-MIMO distributed MIMO.

DL downlink.

DOA direction-of-arrival.

DSF distributed service federation.

ECSP edge computing service point.

EN energy neutral.

END energy neutral device.

ESL electronic shelf label.

FA federation anchor.

FH fronthaul.

GFRA grant-free random-access.

HARQ hybrid automatic repeat request.

IoT Internet of Things.

KPI key performance indicator.

LoS line-of-sight.

MCS modulation and coding scheme.

MD miss-detection.

MIMO multiple-input multiple-output.

MISO multiple-input single-output.

MMSE minimum mean square error.

mMTC massive machine-typed communication.

MPC multipath component.

NLoS non-line-of-sight.

NMSE normalized mean square error.

NR New Radio.

OFDM orthogonal frequency-division multiplexing.

OLoS obstructed line-of-sight.

OMA orthogonal multiple access.

OTA over-the-air.

PA power amplifier.

PAPR peak-to-average power ratio.

PL path loss.

RE radio element.

RF radio frequency.

RFID radio frequency identification.

RMSE root-mean-square error.

RW RadioWeaves.

SER symbol-error rate.

SISO single-input single-output.

SLAM simultaneous localization and mapping.

SNR signal-to-noise ratio.

TOA time-of-arrival.

UE user equipment.

UL uplink.

ULA uniform linear array.

URLLC ultra-reliable low-latency communications.

UV unmanned vehicle.

VNA vector network analyzer.

WPT wireless power transfer.

Chapter 1

Introduction

This deliverable summarizes the results derived from the task dealing with the assessment of achievable gains in deployment scenarios. The goal is to present a concise summary of the potential of RadioWeaves (RW) infrastructure. To this end, this deliverable presents how key performance indicators (KPIs), as the measurable performance values, can be related to different use cases, representing the environment specific interactions and services provided to the user via the RW infrastructure. The use cases are briefly revisited here, also indicating the corresponding cluster association described in [D1.1].

⬛. . . Cluster 1, 🟦. . . Cluster 2, 🟥. . . Cluster 3, 🟩. . . Cluster 4

⬛ *(1) Augmented reality for sport events:* Real-time data and information is presented to users, expected devices are smartphones.

🟦 *(2) Real-time digital twins in manufacturing:* Targeting Industry 4.0 applications, this use case aims at creating digital twins up to the level of full factories, latency requirements are more stringent.

🟩 *(3) Patient monitoring with in-body and wearable sensors:* Improvements are expected for both patients and healthcare staff due to more efficient information collection, also remotely.

🟦 *(4) Human and robot co-working:* Maintaining the safety of human workers will be key, robots are expected to move at high speed, reliability and accuracy of positioning are essential.

🟥 *(5) Tracking of goods and real time inventory:* The field of logistics is expected to profit from the streamlined availability of real-time information of items along the full supply chain.

🟥 *(6) Electronic labelling:* Especially for energy neutral devices that are often used as labels in stores, providing services of wireless power transfer, localization and communication to many devices is a key factor.

⬛ *(7) Augmented reality for professional applications:* Important aspects are the off-loading of the processing load from light weight, low power devices to the infrastructure, enabling cost and complexity reduction of augmented reality (AR) devices.

🟩 *(8) Wander detection and patient finding:* Risks of patient accidents can be lowered while simultaneously giving patients more freedom due to additional security measures possible, patient privacy is and important factor for the applicability at specific locations.

🟩 *(9) Contact tracing and people tracking in large venues:* Automating contact tracing is important in the case of emergencies, while the privacy of the individuals needs to be guaranteed.

🟦 *(10) Position tracking of robots and UVs:* Robots and unmanned vehicles (UVs) exhibiting high mobility require low latency and high positioning accuracy.

🟩 *(11) Location-based information transfer:* Information can be provided as a service, easing everyday life by complementing and updating information about the surrounding.

⬛ *(12) Virtual reality home gaming:* Low latency is important to allow for an immersive experience for the user, alongside high data rates for wireless connections.

🟥 *(13) Smart home automation:* As a growing market in recent years, automation of different aspects of users' home serve personal security as well as efficient use of resources such as heating, cooling or watering systems. High positioning accuracy can be complemented by environment learning.

In [D1.1], clusters of use cases were reported, classifying the use cases according to the involved challenges. The clusters and corresponding use cases are *High traffic volume latency* (Cluster 1 marked as ⬛ containing use cases 1, 7 and 12), *High reliability, low latency high mobility* (Cluster 2 marked as 🟦 containing use cases 2, 4 and 10), *Low energy devices, massive numbers of devices, high accuracy positioning* (Cluster 3 marked as 🟥 containing use cases 5, 6 and 13) and *Mobility, complex environments, positioning, low energy* (Cluster 4 marked as 🟩 containing uses cases 3, 8, 9 and 11). In this deliverable, these essential requirements derived in [D1.1] are further refined, grouped into similar application fields that will each be discussed in a separate section. For each field the use cases and KPIs will be related via groups of publications that contribute to the understanding or achieving of KPIs. The applications are separated into the fields positioning, energy neutral devices, initial access, data rate, latency, synchronization, multiple access, back/fronthaul and device mobility. These relate directly to the four clusters of use case challenges that were worked out in [D1.1], but allow a more detailed analysis within the corresponding fields. While all of the use cases rely on specific capabilities of the RW infrastructure, it became clear that location-based information transfer (use case 11) does not serve this purpose as other use cases, as it mostly relies on the resulting positioning accuracy. Ultimately, another use case will have applied *before* information transfer comes into effect, and we thus do not see the need to explicitly analyze use case 11 here.

Apart from the different application fields, this deliverable will also set the different devices classes introduced in [D1.1] into context of the each application. This will allow to describe specifics of each (or the applicable) device classes, that might require special considerations when used in the respective applications. This will be important when, e.g., a selected algorithm would raise the level of requirements above what is possible with a certain device class, allowing to adapt either the use case or the target requirement to realistic levels. By connecting all of this in the final deliverable of WP1, a broad overview of value of the project can be given in a concise manner.

We will end this deliverable, not only with the accustomed conclusion in form of the distinguishing results, but also will give these stronger context by also outlining possible limitations. We decided for this critical comparison to support and ease future developments related to RW, by providing the detailed picture that was assembled by the consortium over the course of the project.

Chapter 2

Discussion of Use Cases

This chapter discusses the use cases and corresponding KPIs covered by RW by specifically analyzing dedicated application fields. These application fields are

[P] positioning requirements (see Sec. 2.1),
[EN] the operation of energy-neutral devices (see Sec. 2.2),
[IA] initial access to support a large number of devices (see Sec. 2.3),
[DR] peak data rate requirements and aggregate data rate (see Sec. 2.4),
[LL] low latency requirements (see Sec. 2.5),
[SR] synchronization requirements (see Sec. 2.6),
[MA] multiple access (see Sec. 2.7),
[BF] backhaul/fronthaul requirements (see Sec. 2.8), and
[DM] device mobility (see Sec. 2.9).

In each of the corresponding sections, we will introduce the main technical contributions and key findings, presented in form of a table that intersects use cases and KPIs by means of groups of publications and deliverables that contribute to both. For clarity, we will only include use cases that are related to a corresponding KPI by a group in the corresponding tables. Nonetheless, to complement these tables, an extensive table will be made available alongside this deliverable as a spreadsheet. These tables will always be followed by the same general structure of the remaining sections, covering the relation to infrastructure, devices, and developed or tested algorithms.

2.1 Positioning requirements

Positioning services and position-based services require an accuracy between $0.1\,\mathrm{m}$ and $1\,\mathrm{m}$, depending on the specifics of the use case [D1.1]. Comparing these with carrier frequency values of interest $f_c = \{900\,\mathrm{MHz}, 2.4\,\mathrm{GHz}, 3.8\,\mathrm{GHz}, {>}5\,\mathrm{GHz}\}$ and the corresponding wavelength as $33\,\mathrm{cm}$ $(900\,\mathrm{MHz})$, $13\,\mathrm{cm}$ $(2.4\,\mathrm{GHz})$, $8\,\mathrm{cm}$ $(3.8\,\mathrm{GHz})$ and $<6\,\mathrm{cm}$ $({>}5\,\mathrm{GHz})$, shows that especially in the high frequency bands the targeted (high-level) accuracy is below the corresponding wavelength. In combination with the limited bandwidth of $<100\,\mathrm{MHz}$, a large spatial aperture is necessary to achieve these accuracy values, i.e., physically large antenna arrays with a large number of antennas that allow forming narrow beams in the far-field or small focus points in the near-field of the respective antenna arrays. This was shown to be feasible in [D3.3, Ch.3] where the effect of the array geometry at the contact service point (CSP) in combination with the processing of parts of the aperture was analyzed. Intuitively, the relation of the achievable positioning accuracy and the wavelength can be drawn in a straightforward manner by converting the accuracy bounds into (fractions of) wavelengths. Nonetheless, it should be noted that the contribution of angle estimation (or consequently of the spatial aperture in the array near-field) to the overall achievable accuracy depends on the carrier frequency only indirectly when assuming the inter-element spacing to be linked with the carrier wavelength, e.g., using $\lambda/2$-spaced uniform arrays. Especially in close proximity to an array, the angle-estimation contribution to the overall position information surpasses that of the range-estimation contribution, as the former is inversely proportional to the distance [1, 2]. Thus, being in close proximity to the CSPs, either in an absolute sense due to a densely distributed network of CSPs, or a relative sense due to the CSPs exhibiting a large physical size, is seen as the main enabler of RW infrastructure to achieve the targeted accuracy regimes.

2.1.1 Main technical contributions and key findings

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
2	Real-time digital twins in manufacturing					[P2]			[P1] [P2]				
5	Tracking of goods and real-time inventory					[P2]	[P1]		[P1]				
6	Electronic labelling	[P3]				[P3]	[P3]					[P3]	
10	Position tracking of robots and UVs					[P2]	[P1]		[P1]				
13	Smart home automation								[P1]		[P1] [P2]		

Table 2.1: Positioning requirements connecting use cases and KPIs in publications.

The main technical contributions are assigned to use cases and KPIs in Table 2.1. Publications and deliverables that are of importance for achieving or analyzing the positioning requirements for use case-KPI combinations are grouped as follows.

- [P1] covers positioning aspects including fundamental performance limits with related papers [3, 4] and [5] and deliverables [D3.3, Ch. 3] and [D3.3, Ch. 4].

- [P2] covers channel modeling and situational awareness, encompassing environment-learning-related aspects with related papers [6], [7], [8] and [9], and deliverables [D3.4, Ch. 3] and [D5.3].
- [P3] covers the operation of energy neutral devices (ENDs), including power transfer, initial access, backscatter channel estimation, and positioning with related papers [10], [11], [12], [13], [14] and [15].

2.1.2 Relation to infrastructure

The analysis of fundamental performance limits from [D3.3] allows to investigate the achievable positioning performance of a given infrastructure from a geometric point of view, and regarding signal and system specifics such as bandwidth and carrier frequency. It was shown that the spatial distribution of the achievable positioning accuracy can be tailored to applications, by distributing more CSPs in regions where a higher accuracy is targeted. This was shown using numerical simulations in [D3.3]. This was further studied in [4], where an algorithm for optimum anchor placement was analyzed.

The effect of the level of synchronization of the infrastructure can be validated in a similar manner, with a comparison between the fully coherent use of large arrays and non-coherent combination of coherent sub-arrays both showing the capability to achieve an accuracy between $0.1\,\mathrm{m}$ and $1\,\mathrm{m}$ for the targeted channels.[1]

The inherent robustness benefits of distributed radio infrastructures were also shown in the direct-simultaneous localization and mapping (SLAM) algorithm used in [14], allowing to counter obstructed line-of-sight (OLoS)[2] conditions to some single-antenna CSPs through Bayesian filtering leveraging delay-Doppler direct positioning. Planar positioning root-mean-square errors (RMSEs) of $10.1\,\mathrm{cm}$ and $11.5\,\mathrm{cm}$ was achieved with only some CSPs in OLoS conditions, and $49\,\mathrm{cm}$ where for parts of the track *all* CSPs were in OLoS conditions. It is important to note that Doppler-based positioning requires device mobility.

The robustness of a RadioWeaves infrastructure is not solely due to its distributed nature. Environment learning with distributed CSPs is another feature of RadioWeaves, that enables high robustness and positioning accuracy as we have demonstrated with the direct-SLAM algorithm in [D5.3]. Leveraging angular-delay direct positioning, we are able to jointly infer the device position and geometric position and orientation of two walls in the scenario. Using Bayesian state-filtering, we are able to exploit non-line-of-sight (NLoS)[3] paths via the learned environment geometry to accurately position the device even in total OLoS conditions. Despite a low input signal-to-noise ratio (SNR) $\leq -6\,\mathrm{dB}$ in LoS conditions and an even much lower SNRs in total OLoS conditions, we achieve a planar position RMSE of as low as $6.5\,\mathrm{cm}$ on our real-world measurements.

2.1.3 Relation to devices

Positioning of active user equipments (UEs) is a well-studied topic in literature, covered by a multitude of different more or less specific scenarios and infrastructure configurations [16, 17, 18].

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[1] We refer to a channel as a combination of center frequency and bandwidth.

[2] We use the term obstructed line-of-sight to define the channel condition where the line-of-sight (LoS) path is obstructed by an object.

[3] We use the term non-line-of-sight to define the propagation of a ray cast by the transmitter that does not take the direct LoS path to the receiver but a multipath via at least one object where it is reflected.

Similarly, passive localization in the context of backscattering, e.g., radio frequency identification (RFID) devices [19], or battery-less [20] or energy-neutral devices is a growing topic. This section discusses implications for the various device classes of interest.

Energy neutral devices (ENDs) - class 1, 2 and 3 Positioning different classes of ENDs [D1.1, Sec. 3.1] generally requires an initial access step, i.e., performing wake-up of the device at the unknown position. The device class indicates whether the device is capable of storing energy or not, i.e., class 1 and 2 devices only perform backscatter communication and have no or only limited power storage capabilities, hence require being supplied with energy via wireless power transfer (WPT), whereas class 3 covers ENDs that can also actively transmit signals, while being charged wirelessly via WPT as well. Especially devices of class 1 and class 2 are difficult to embed in position applications, as they are only capable of backscatter communication in the uplink, and thus require WPT towards their actual location with no or very limited prior information. The initial access problem of such devices is covered in [10] where location-based beamforming schemes for initial access are analyzed, also treating the effect of (partial) environment knowledge. Based on realistic simulations we showed in [10] that various beamforming schemes allow significant power transfer over distances of $8\,\mathrm{m}$ and above, with beam diversity helping to overcome fading effects in the vicinity of the END. Based on real-world measurements, we demonstrated that milliwatt-level receive powers are achievable even under regulatory constraints when exploiting physically large, e.g., much larger than a wavelength, or distributed apertures on the infrastructure side.

The large "two-way" path loss (PL) incurring with backscatter-based energy neutral (EN) devices may put the receive-side infrastructure in a severely low input SNR regime, which likewise severely impacts the efficiency of a reciprocity-based beamformer. Using our direct-SLAM approach [D5.3], in the *channel estimation* step, we have demonstrated that we can achieve a planar positioning RMSE of around $6.5\,\mathrm{cm}$ despite an SNR $\leq -6\,\mathrm{dB}$ and severe OLoS conditions, which is possible by learning the environment geometry (i.e., walls) and positioning the EN device in OLoS conditions via NLoS multipath components reflected off these walls. In the *channel prediction* step, we have shown that our algorithm outperforms a reciprocity-based beamformer by up to $5\,\mathrm{dB}$ which means a power transfer efficiency improvement by a factor of 3.13. Our algorithm is even able to predict geometry-based channel state information (CSI) to future time steps, where the performance gap to a reciprocity-based beamformer given outdated CSI is even more severe.

2.1.4 Algorithms

Algorithms profit from distributed infrastructure, i.e., multiple CSPs with close-to-the-edge processing capabilities. This allows to perform local computations simultaneously, e.g., parametric channel estimation at a selection of CSPs, freeing additional resources for other applications. In contrast, channel non-stationarity due to limited visibility of multipath components is described in [D1.2] and [6]. Common algorithms candidates for positioning and tracking of mobile devices are based on Kalman or particle filter implementations. In [D3.3] the capabilities of an extended Kalman filter were analyzed in combination with varying levels of LoS conditions along an array. Especially when a large portion of a physically large CSP is in LoS, the achievable accuracy is in the targeted region of $0.1\,\mathrm{m}$, whereas NLoS regions require additional infrastructure or wider distribution of existing infrastructure, or the use of environment information to allow exploiting position-related information contained in specular multipath components (MPCs). The case of distributing the infrastructure to overcome NLoS channel conditions was applied successfully in

[14] to distributed multiple-input multiple-output (MIMO) scenario.

A two-step approach, i.e., estimation of position-related parameters such as direction-of-arrivals (DOAs) and time-of-arrivals (TOAs) at different locations followed by a data fusion step to combine the separate estimates into a joint position estimate, is well suited for parallelizing tasks at different locations, e.g., at CSPs or edge computing service points (ECSPs). This enables a modular system structure allowing to exchange parts of the processing chain where necessary, or to fine-tune performance.

Our direct-SLAM algorithm from [D5.3] operates at the fifth-generation (5G) New Radio (NR) band n78 with a center frequency of $f_\mathrm{c} = 3.55\,\mathrm{GHz}$ and a bandwidth of $B = 500\,\mathrm{MHz}$ [21]. Experimental data have been acquired through synthetic aperture vector network analyzer (VNA) measurements in a realistic hallway scenario. We have demonstrated that we were able to accurately estimate the three-dimensional (3D) position of the moving device with a planar position RMSE of $6.5\,\mathrm{cm}$ despite total OLoS conditions and a low input SNR of $\leq -6\,\mathrm{dB}$. Additionally to the device position, the distributed CSPs jointly infer the geometrical position and orientation of walls which is the feature enabling our algorithm to perform accurate positioning as the device moves into OLoS. Geometry-based spherical-wavefront multipath (i.e., NLoS) beamforming [7] enables higher data rates and more efficient power transfer. Our channel fusion method constitutes a probabilistic combination of noisy measured CSI with geometry-based predicted CSI. While it may come at the cost of some efficiency, it provides resilience against outages, i.e., it prevents deep fades caused by outdated measured CSI or through a wrong position estimate [D5.3] or mismatched geometric channel model [D4.3].

> *An overall large aperture is an enabler for the use of **flexible** subarray-based approaches for positioning and environment learning. This allows to deal with non-stationary propagation conditions and can help overcome the increasing complexity of super resolution algorithms applied to signals containing a large number space-time/frequency samples by processing only a portion of the data at each subarray.*
>
> *Holistic algorithms employ channel estimation and -prediction to improve the beamforming **efficiency** of a geometry-based beamformer over a reciprocity-based beamformer given noisy measured CSI.*
>
> *Even under high device **mobility**, leveraging a motion model enables CSI prediction to future (even non-integer) time steps, increasing the performance advantage of a geometry-based beamformer over a reciprocity-based beamformer given outdated CSI even further.*
>
> *Environment learning, i.e., estimation of the geometric position and orientation of walls using the radio signal, enables **robust** and **accurate** NLoS positioning even when a device is in total OLoS conditions.*
>
> *Channel fusion, i.e., the probabilistic combination of measured and predicted CSI, trades some efficiency for a better outage **resilience**.*

2.2 Energy neutral operation of devices

In the REINDEER project, research is conducted into radio frequency (RF) WPT techniques to deliver energy over the air to depleted nodes. Devices with low energy requirements can be implemented in a fully energy-neutral manner in future use cases. Distributed antenna setups are utilized for this purpose. This section mainly considers the class 1 and class 2 EN devices from the 5 device classes outlined in deliverable [D1.1]. Section 2.2.1 lists all contributions related to energy-neutral operation specifically from the partners involved in WP2 and WP4. The publications related to the infrastructure and the devices are presented in Sections 2.2.2 and 2.2.3, respectively. The final part in Section 2.2.4 references several algorithms.

2.2.1 Main technical contributions

Use cases from [D1.1] that could be designed as battery-less or energy-neutral devices include (4) Patient Monitoring, (6) Electronic Labelling, (8) Wander detection and patient finding, (9) Contact tracing and people tracking in large venues and (13) Smart home automation. The corresponding conference and journal publications, along with the relevant deliverable sections, are consolidated into four topics and referenced in Table 2.2.

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
3	Patient monitoring with in-body and wearable sensors									[EN4]			
4	Human and robot co-working	[EN3]								[EN4]		[EN1] [EN2]	
5	Tracking of goods and real-time inventory									[EN4]			
6	Electronic labelling	[EN3]				[EN3]				[EN4]		[EN1] [EN2]	
8	Wander detection and patient finding	[EN3]								[EN4]		[EN1] [EN2]	
9	Contact tracing and people tracking in large venues	[EN3]								[EN4]		[EN1] [EN2]	
13	Smart home automation	[EN3]								[EN4]		[EN1] [EN2]	

Table 2.2: Energy neutral operation of devices connecting use cases and KPIs in publications.

- [EN1] combines several research topics to realize energy-neutral devices. The **RF WPT technology** is explained in [D4.1, Ch. 2], a WPT review journal is retrievable in [22] and an alternative remote WPT solution is available in [23]. The **hardware guidelines** are divided into two separated designs. END design proposals are retrievable in [D4.1, Ch. 5], [D4.2, Ch. 5], [D4.3, Ch. 5] and [24] and design guidelines for an CSP acting as a charging element to support WPT is covered in [D2.3, Ch. 5]. **Near field beamforming** approaches to supply ENDs is covered in several deliverables. The investigated WPT channel models are covered in [D4.1, Section 2.2], [D4.2, Section 2.1], [7] and the WPT power budget simulations are presented in [D4.1, Section 4.1] with verifying measurements in [D4.2, Section 2.1]. **Synchronisation** challenges for distributed WPT are elaborated in [D2.2, Ch. 2] and [D2.3, Ch. 4].

- [EN2] includes **initial access** research in [D4.2, Ch. 4],[10, 11], a theoretical view combined with simulation in [D4.1, Section. 4.1.2] and measurements in a conference publication [22].
- [EN3] deals with **feasibility studies** to supply power to use cases in [D2.3, Sections 2 and 3] and conference publications in [25, 26].
- [EN4] covers **backscatter communication** to achieve energy neutral operation. Uplink (backscatter) data transfer communication is introduced in [D4.1, Section 4.2.3] and [D2.3, Ch. 6]. More in depth studies can be found in [D4.2, Ch. 3], [D4.3, Ch. 3], [27] and [28].

2.2.2 Relation to infrastructure

Reciprocity-based beamforming requires a compatible infrastructure with challenging phase synchronization across the distributed CSPs. [D2.2, Ch. 2] describes the various synchronization options along with the associated challenges. Guidelines regarding the RF front-end of the CSP were proposed in [D2.3, Ch. 5]. The most challenging electronic shelf label (ESL) use case was elaborated in [D2.3, Sections 2 and 3] to gain insight into the power that the power amplifiers (PAs) need to support. More refined analyses were published in [25, 26]. In [26], it was demonstrated how the entire efficiency can be increased using the same infrastructure by solving an optimization problem, effectively minimizing the total transmit power while optimizing the energy transmitted towards the receivers.

2.2.3 Relation to devices

[D1.1] describes several use cases that are assumed to be produced without batteries in the future. The most challenging ESL use case is elaborated in [D2.3]. Consequently, it is assumed that other use cases with lower energy requirements can be supported. Similar feasibility studies supporting energy-neutral ESLs are presented in [25, 26].

2.2.4 Algorithms

Power budget estimation/prediction: In [D5.3], we have demonstrated that our direct-SLAM algorithm is capable of predicting CSI to future time steps, which in turn can be used to generate estimates for the power budget at future time steps. Our algorithm in its current implementation estimates new component (LoS and NLoS) amplitudes per time step. The amplitudes for these components are nuisance parameters that we assume to evolve independently in each step, i.e., a new amplitude is estimated per component of each time step. These amplitudes are not part of the state vector of our state-space filter and hence they are not filtered using our current method of power budget prediction, which is why the predicted channel degrades in a low-SNR scenario. We can show that the power budget can be predicted very accurately to future time steps in higher SNR with our method.

In a similar fashion, tracking of a mobile backscatter END allows to use the downlink (DL) transmissions towards the predicted position of the device to perform WPT, and update the predicted position with estimates obtained from the resulting uplink (UL) transmission. By improving the position estimate/prediction, also the WPT efficiency in the DL and consequently the SNR will increase.

Initial access: All batteryless EN devices operating through backscatter communication rely on solving the initial access problem, i.e., beamforming sufficient power to the device without being able to receive an uplink before the initial wake-up of the device. The REINDEER consortium has investigated several different methods (i.e., algorithms) ranging from CSI-free methods like random beamforming [25, 29], good for waking up massive numbers of devices with low efficiency, and exhaustive codebook searches [D5.3], possibly very efficient yet very time intensive, to CSI-based methods like geometry-based beamforming [10, 11] used in conjunction with a spatial search, called a beam sweep.

In [22], the ceiling of the Techtile testbed was configured to generate multi-tone and adaptive sine non-coherent signals. The energy was measured at a static position using an energy profiler with the embedded NXP harvester. Both signals designs are compared and adaptive single-tone signals provides on average the highest harvester efficiency levels. A Monte Carlo algorithm was then used to analyze the response time of the energy-neutral device during this initial access phase.

Robust and efficient beamforming under device mobility: After the initial access to a batteryless EN device has been established, ensuring a constant influx of wireless power to ensure operability is of utmost importance. For instance, if a reciprocity-beamformer is employed to power an EN device that is moving out of the “main beam” into a “null” in between two consecutive pilot transmissions, it will not receive any power it could backscatter, the internal capacitor may deplete, current CSI is unknown, communication ability is lost and the initial access procedure must start again. To overcome this problem, our holistic environment-aware algorithms[4] [D5.3] perform both channel *estimation* and *prediction* as well as *environment learning* to detect and bypass OLoS conditions via multipath beamforming enabled through the learned environment geometry. Our algorithms have proven the ability to predict CSI multiple (even non-integer) time steps into the future, where the respective geometry-based beamformer outperforms a reciprocity-based beamformer given outdated CSI by a large margin.

It should be noted that while CSI-based beamforming has no means of compensating for changing characteristics of the device mobility, position-based approaches will allow joint estimation of the device mobility, e.g., allow to select a motion model fitting to the application to improve the accuracy of the predicted position, and consequently both robustness and efficiency.

Use case related: Making optimal use of the infrastructure’s resources is crucial for achieving more efficient energy transmission. In [26], an optimization problem for total transmit power and delivered energy was presented for the ESL use case, addressing both coherent and non-coherent wireless power transfer solutions.

Backscatter communication: Algorithms in the field of reducing direct link interference in backscatter communication are presented in [D4.2, Ch. 3], [D4.3, Ch. 3] and [27, 28].

---

[4] Our direct SLAM and closed-loop approach.

2.3 Initial access supporting many devices

In this section, the algorithms and techniques to provide initial access to support many devices in REINDEER are described. A distinction is made between techniques focussing on providing i) massive access, i.e., a high number of potential devices simultaneously requiring access and ii) initial access. The latter involves signalling and powering devices prior to start requesting access to the network. The technologies below can be applied to different use cases. These technologies are grouped and included in the table in Section 2.3.1.

2.3.1 Main technical contributions

2.3.1.1 Initial Access for Energy-Neutral Devices

Channel state estimation can be performed on the first signal sent by an EN device, possibly through backscatter communication [30], which can be performed efficiently when EN devices start up in class 0 mode [31]. With no array gain available, supplying an EN device with sufficient power to exceed the device sensitivity, *i.e.*, the minimum power required for wake-up and backscatter communication [32], strongly reduces the initial access distance.

To achieve initial access and/or to improve the energy transfer, the impact of antenna deployment and different waveform and beamforming strategies are investigated in the project. Each strategy has different synchronization and END class requirements. We envision that practical systems will be a hybrid, where ENDs are being charged through CSI-free methods, until a pilot is sent, and the system can operate in a fully coherent stage.

2.3.1.2 Massive (Random) Access

Two strategies are explored in regard to massive random access: i) grant-based and ii) grant-free random access. Before getting resources in the network, the devices need to exchange information and request access to resources for communication. In grant-based random access, the devices use a random access channel to obtain a grant to the requested resources. Alternatively, devices can just send their information without requiring a grant. The network needs to detect and resolve collisions. The latter strategy is often used in Internet of Things (IoT) networks, to minimize the transmit energy at the IoT device. The main technical contributions are assigned to use cases and KPIs in Table 2.3.

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
4	Human and robot co-working	[IA2]					[IA3]	[IA3]					
6	Electronic labelling	[IA2]								[IA1]	[IA1]	[IA1]	

Table 2.3: Initial access, connecting use cases and KPIs in publications.

- [IA1] contains publications [29, 25, 10, D3.2, D5.3, 33, 34] dealing with initial access for energy neutral devices.

- [IA2] contains publications [D3.2, 35, 36, 37, 38, 39, 40] dealing with the operation of massive numbers of devices.
- [IA3] [D3.2, Chapter 6] relates to initial access schemes tailored to ultra-reliable low-latency communications (URLLC).

2.3.2 Relation to infrastructure

In relation to the infrastructure, we differentiate between

1. geometric properties, e.g., array layout, and
2. system properties, e.g., signalling schemes that can be implemented.

Impact of Antenna Deployment Topology on Performance of Grant-Free Access Detection Methods

We considered two deployment strategies, co-located and RadioWeaves deployments, to study the impact of antenna deployment topologies on the grant-free random access performance. For co-located reference case, we considered a candelabrum type deployment on the ceiling or the wall with the antennas pointing in every corner in the room and thus, this shape guaranteed that we have coverage at every part of the room. For a RadioWeaves deployment, we considered 4 uniform linear arrays (ULAs) on the walls of the room. We observed that the RadioWeaves deployment performed much better than co-located deployment, owing to the fact that the spatial resolution between the users is improved by using RadioWeaves [D3.2, 35, 36].

> *The infrastructure should follow the RadioWeaves architecture, where the antennas are distributed around the intended users.*

Multi-versus Single-Tone Transmission for initial access of ENDs

Without any prior information of the location of the END or CSI, beamforming is not possible. To wake up the device, i.e., initial access, other strategies are proposed. In [29], the efficiency of waking up and charging an END is investigated with single- and multi-tone signals. We experimentally demonstrate that single-tone transmission with adaptive phase changes outperforms conventional multi-carrier waveforms for ENDs with state-of-the-art energy harvesters.

> *The infrastructure should be able to frequently change the transmit phases to induce large fluctuations in the received power levels. In this case, the CSPs only needs to be frequency synchronized.*

2.3.3 Relation to devices

Strategies to provide initial access depend on the device class [D1.1, Sec. 3.1]. The device class indicates whether the device is capable of storing energy or not, i.e., class 1 and 2 devices only perform backscatter communication and have no or only limited power storage capabilities, hence require being supplied with energy via WPT, whereas class 3 covers ENDs that can also actively transmit signals, while being charged wirelessly via WPT as well.

In Section 2.3.2, we assumed that the END has insufficient power to transmit a pilot. However, class 3 ENDs are able to transmit pilots without prior WPT and hence do not necessarily rely on an initial access phase without CSI. In [41], the obtained gains when having CSI and no prior information is studied.

> *In case there is no CSI or other prior information available, class 1 and 2 devices require the infrastructure to transmit with higher powers compared to (coherent) beam focussing. The initial access can be improved by designing a dual-harvester ENDs. In that case, a dedicated circuit could be designed for very low receive power tailored for pilot transmission, after which the secondary harvester is used during coherent downlink WPT.*

2.3.4 Algorithms

The researched algorithms concerning initial access in REINDEER are described per stage:

- Initial access strategies to provide sufficient power to ENDs
- When having a sufficient power source to provide signalling, random access to retrieve network information and get access to the network for communication.

2.3.4.1 Initial Access of Waking-up ENDs

During the initial-access phase, *measured* CSI is unavailable. Reciprocity-based beamforming relies on measured CSI and is therefore no option before the initial power-up of the END.

However, while coherent, i.e., CSI-based beamforming (cf. [34, 11]), is a more efficient method for powering a few devices (either sequentially using a single beam transmission or simultaneously using a multibeam transmission), CSI-free methods are more efficient when powering many distributed devices which has been proven both in related literature [42] and in research conducted by the REINDEER consortium [25].

An overview of the studied approaches to wirelessly power ENDs during initial access in REINDEER are summarized in Table 2.4. In this table, the required synchronization capabilities of the infrastructure is detailed.

Table 2.4: Overview of WPT (initial access) strategies and their requirements needed to provide RF WPT.

	Sync. Requirements			
RF WPT Strategy	Time	Freq.	Phase	Other prior info
CSI-based methods	✓	✓	✓	-
Environment-aware Initial Access	✓	✓	✓	environment and position of END
CSI-free methods	✓	✓	✗	-
Exhaustive codebook methods	✓	✓	✓/✗	In case of spatially sweeping, the array needs to be phase calibrated. Otherwise, not.

CSI-based methods for WPT

In the following sections we assume *phase calibration*, i.e., knowledge of the systematic phase errors introduced by the physical hardware (including passive components such as cables, connectors, and antennas). For phase-coherent CSI-based beamforming, the wavefronts of signals transmitted by multiple physical antennas are controlled such that they constructively interfere at the receiver (e.g., END) position, hence all phase errors in the hardware need to be accounted for including the phase shift due to the signal distance traveled between both physical antennas. When mentioning the prerequisite of *phase calibration* this generalizes from phase coherent beamforming with a single array (and a single clock) to possibly phase coherent beamforming with distributed arrays (and multiple clocks) given that the clocks are frequency synchronized and the phase-differences between the individual clocks are known (or estimated).

> *Imperfect phase calibration, i.e., incomplete knowledge of the phase errors, results in a "synchronization" loss derived in [D3.2, Sec. 4.1.2].*
>
> *Beam diversity can be effectively exploited to even out deep fades and generate a smoother power distribution in proximity of the focal point. [10, D3.2]*
>
> *Holistic algorithms exploit channel estimation (i.e., positioning and environment learning) and prediction (i.e., geometry-based beamforming), which outperforms reciprocity-beamforming in low-SNR regimes through the incorporation of physics-based knowledge [D5.3].*
>
> *Leveraging a motion model under device mobility, both the future device position and its channel can be predicted to future time steps where the performance advantage of a geometry-based beamformer gets even more significant over the performance of a reciprocity-based beamformer given outdated measured CSI [D5.3].*

Environment-aware Initial Access to EN Devices

Under the prerequisite of a phase-calibrated array, CSI can be *predicted* based on a known END position relative to the array for LoS beamforming, and can exploit a known environment geometry for NLoS beamforming (cf. [33, Sec. 2.2], [34]). Unfortunately, the END position is likewise an unknown parameter during the initial access phase and may necessitate an exhaustive parametric search, also known as a beam sweeping. Using measurements in a realistic environment, we have demonstrated that high beamforming efficiencies are achievable using such geometry-based beamformers [7]. However, they come at the cost of beam sweeps that are possibly long and resource intensive. We showed that a plane-wave beamformer may be a viable alternative for certain applications to a spherical-wavefront beamformer trading some efficiency for a smaller search space (cf. [43, Fig. 2.6]).

> *In systems that involve large numbers of antennas, a good geometry-based channel model may yield accurate CSI that can leverage most of the available array gain (cf. [43, Fig. 2.2]).*

CSI-free methods for WPT

Most CSI-free methods do not rely on the assumption of a phase-calibrated array. Furthermore, recent research shows that beamforming to massive numbers of devices may be more efficient when employing CSI-free beamforming [42, 25].

Exhaustive codebook searches Exhaustive codebook searches may employ a search over the "phase space" of the transmit antennas used. While it does not rely on a phase calibration, it comes at the price of a very large codebook and possibly long search time. One possible algorithm may be to search in 90° phase steps at each antenna $n \in \{1 \dots N\}$ resulting in a codebook size of 4^{N-1} (only the $N-1$ phase differences matter, one phase can be kept constant).

> *This method may yield large array gains, but is only feasible for small numbers of antennas because of the codebook size growing exponentially with N.*

Random beamforming We found that the random beamforming efficiency performs on expectation only as well as an equivalent single-input single-output (SISO) system (cf. [43, eq. (2.15)]). However, a gain of up to $6\,\mathrm{dB}$ is achievable within $98\,\%$ of the random beamforming weight realizations (cf. [43, Fig. 2.2]). While this may only be a small portion of the available array gain (equal to the number of transmit antennas N), it may be sufficient to wake up ultra-low power ENDs in a class 0 mode (cf. [31, Sec. 3.1]).

> *Furthermore, it is the preferred option for powering large numbers of ENDs even after the initial access [42, 25] and thus in massive device deployment scenarios this seems to be the beamforming method of choice.*

2.3.4.2 Random Access

In this stage, the devices are powered and trying to get access to the network. The first challenge in random access is to get sufficient information regarding the network they are trying to connect to. The second challenge is to obtain a resource to transmit or receive data to and from the network, which can be obtained by using grant-free or grant-based approaches.

Random Access and Broadcast Information for Communication

Broadcast Information In centralized MIMO systems, beam-sweeping is often used to cover an area with transmissions providing broadcast information. This works well when the number of beams a UE need to monitor is reasonably small. For example, beam sweeping with up to 64 beams from each base station is supported in the 3GPP 5G NR standard. However, this approach does not scale well in a distributed MIMO (D-MIMO) deployment, where the UEs are listening to, not one base station, but to many service points at the same time. The number of sweeping beams required to cover an area with system information signalling in a D-MIMO deployment grows with the number of service points. In [D2.3, Sec. 3.1] three different solutions for efficient broadcast in a D-MIMO system are discussed: (1) using a sub-set of the service points for transmission of broadcast information; (2) using dual polarized and array size invariant beamforming [37]; and (3) space-time coding with port hopping.

> *Beamsweeping requires phase-calibrated infrastructure.*

Grant-Free Random Access of IoT devices in Massive MIMO with Partial CSI The number of wireless devices is drastically increasing, resulting in many devices contending for radio resources. In [38, 39], we present an algorithm to detect active devices for unsourced random access, i.e., the devices are uncoordinated. The devices use a unique, but non-orthogonal preamble, known to the network, prior to sending the payload data. They do not employ any carrier sensing technique and blindly transmit the preamble and data. To detect the active users, we exploit partial CSI, which could have been obtained through a previous channel estimate. For static devices, e.g., Internet of Things nodes, it is shown that CSI is less time-variant than assumed in many theoretical works. The presented iterative algorithm uses a maximum likelihood approach to estimate both the activity and a potential phase offset of each known device. The convergence of the proposed algorithm is evaluated. The performance in terms of probability of miss detection and false alarm is assessed for different qualities of partial CSI and different signal-to-noise ratio.

> *In this scenario, the infrastructure should be phase-coherent and the devices should be able to sporadically transmit a pilot uplink.*

Grant-Based Access Techniques For URLLC Applications The design of a URLLC system poses stringent requirements on both latency and reliability. During the random access phase in grant-based systems, a significant delay is caused by the four-step handshaking procedure between the users and the CSPs, whereas in the payload transmission phase, the latency occurs due to a multitude of factors such as packet encoding and transmission, receive processing, and packet decoding. We can improve the reliability by reducing the events of these failures due to preamble collision, poor channel conditions, severe interference, etc. For example, by using efficient preamble allocation and selection, adaptive modulation and coding scheme (MCS), alternative waveforms, dynamic scheduling of CSPs and interfering users, channel quality prediction, and other pro-active measures. Further, we can devise efficient retransmission schemes for the failed preamble/packet such as hybrid automatic repeat request (HARQ). A main challenge for URLLC is the procedure as to how to apply these schemes to improve the reliability while satisfying the constraints on latency and radio resources. We discussed the fundamental limits and the recent advances in these related topics in [D3.2, Chapter 6].

> *In this scenario, the devices should be able to transmit an uplink pilot for resource allocation and the infrastructure should be phase-coherent for reliability and low latency.*

Data-Driven Robust Beamforming for Random Access We proposed a solution which makes use of the knowledge of the historical CSI to improve the link quality (beamforming gain) to a set of candidate locations estimated where the UE may be [40]. The primary idea is to design a codebook of beamforming (or precoding) vectors, to robustly transmit information and/or power to such set of candidate locations. One of our novel contributions is that, from the historical CSI, we form a database of channel responses seen in the past, preferably in chronological order (each response is typically associated with a particular location of the user and a particular time-stamp). Based on this so-obtained set of responses, a codebook of beamforming vectors is determined through the use of an optimization algorithm. This set of beam formers are designed according to a minimax principle, such that they are good for the “worst” among the set of channel responses.

> *In this scenario, the infrastructure has to be phase calibrated to provide a high and robust beamforming gain to a UE in the DL.*

2.4 Peak data rate requirements and aggregate data rate

Key Performance Indicator	Unit	Use Case												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Max # of simult. Devices	1	10k	1k	20	10	50k	10k	10	50	10k	500	100	2	10k
User experience data rate	Mbps	5	1	1	5	1	1	45/3000	1	1	10	10	150	0.5

Table 2.5: Number of simultaneous devices and user experienced data rates for the studied use cases.

The combination of the number of devices and the experienced user data rates determines the aggregated data traffic that an RW infrastructure should be able to handle. The *Human and robot co-working* use case has the lowest aggregate data rate of 50 Mbps, while for *Augmented reality for sport events* the number can be as high as 50 Gbps due to the high number of devices expected in a stadium environment. The real-time nature of the latter use case, with a 20 ms latency requirement, will put very high requirements on the RW infrastructure.

2.4.1 Main technical contributions

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
1	Augmented reality for sports events	[DR1] [DR2]	[DR1] [DR2]										
2	Real-time digital twins in manufacturing		[DR1] [DR2]	[DR2]									
6	Electronic labelling	[DR1] [DR2]	[DR1] [DR2]										
7	Augmented reality for professional applications		[DR1] [DR2]	[DR2]									
12	Virtual reality home gaming			[DR2]									

Table 2.6: Data rate connecting use cases and KPIs in publications.

The main technical contributions are assigned to use cases and KPIs in Table 2.6.

- [DR1] contains publications [44][45] dealing with spectral efficiency, practical user separability, and user rates for D-MIMO in a laboratory environment.
- [DR2] contains the deliverable [D3.1] dealing with peak data rates and sum rates for an RW infrastructure.

2.4.2 Relation to infrastructure

In the *Augmented reality for sport events* use case, the high number of devices has to be met with an even higher total number of radio elements (REs). In terms of individual-user experienced peak data rates, the *Augmented Reality for Professional Applications* use case has the highest requirement with 45 Mbps for compressed video and up to 3 Gbps for uncompressed video, and there the user density is expected to reach 10 devices per 100 m^2. Although the average user density in the stadium environment is at a somewhat lower level (10,000 visitors in a 200 m x 300 m stadium), the sheer number of simultaneous users and the local user density put high demands on the infrastructure, with a total aggregated traffic of up to 50 Gpbs and 10 Mbps/m^2. In the simulated LOS case in [D3.1] it seems reasonable to support a data rate of 3-5 bits/s/Hz per user with a radio stripe deployment along walls with 512 REs in a 40 m x 40 m room with 200 users. This corresponds quite well to the user density in *Augmented Reality for Professional Applications* and results in 5.6 Mbps/m^2 for the compressed video case and 375 Mbps/m^2 for the uncompressed video case. To support this traffic, a bandwidth on the order of 10 MHz and 600 MHz, respectively, would be required, which should be in somewhat realistic regions. The measurements in [44] indicate a sum rate capacity of 30 bits/s/Hz at an SNR of 10 dB with 128 REs and 12 simultaneous users in a lab environment of 15 m x 6 m. This means 2.5 bits/s/Hz per user. Although this rate is not uniformly distributed among users, with 128 REs and zero forcing almost all users get some (i.e., a nonzero) data rate. This indicates that it should be possible to support the 12 simultaneous single-antenna users in the *Augmented Reality for Professional Applications* use case in real channels as well with 20 and 1200 MHz channel bandwidth, respectively. For the uncompressed video case, with the high single-user peak data rate, it would be highly beneficial to have multiple antennas on the user side to allow multiple layers per user to reduce bandwidth requirements. One should also note that for *Augmented reality for sport events* the number of REs must be significantly increased to support the large number of users.

2.4.3 Relation to devices

The critical use cases involve battery-powered, mobile end-user devices with significant energy-storage, computation, and communication capabilities (e.g., smartphones, VR goggles, etc.), with a potential for compute off-loading to the infrastructure.

2.4.4 Algorithms

The evaluations were based on zero forcing processing. Coherent operation with interference nulling appears necessary to support the user densities required.

> *In terms of individual-user experienced peak data rates, the Augmented Reality for Professional Applications use case has the highest requirement with 45 Mbps for compressed video and up to 3 Gbps for uncompressed video. Simulations in [D1.1, Sec. 3.1] and measurements in [44] indicate that it should be possible to support those challenging use cases with reasonable user densities and bandwidths. However, it is a challenge to support extreme data rates as in the case of uncompressed video for many simultaneous users without increasing the number of antennas at the device side. For the Augmented reality for sport events use case the number of REs have to be scaled up significantly to be on par with the number of spectators.*

2.5 Low latency and reliability requirements

Key Performance Indicator	Unit	Use Case												
		1	2	3	4	5	6	7	8	9	10	11	12	13
End to end latency	ms	20	1	200	1	100	1000	10	1000	1000	10	1000	10	100

Table 2.7: End to end latencies for the different use cases.

Low end-to-end latency is one of the most critical and demanding requirements, that has the potential to strongly influence how RW is designed and how nodes in the infrastructure can co-operate to process and deliver services. The strictest requirements come from the *Real-time digital twins in manufacturing* and *Human and robot co-working use cases* with end to end latencies of max 1 ms. Propagation delays are a minor contribution to the total latency, where 1 ms corresponds to about 300 km. There are, however, other inter-linked bottlenecks that need to be investigated in greater detail, and in combination, when designing the infrastructure, as described below.

2.5.1 Main technical contributions

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
2	Real-time digital twins in manufacturing	[LL2]				[LL2]	[LL1] [LL2]	[LL1] [LL2]	[LL2]				
4	Human and robot co-working					[LL2]	[LL1] [LL2]	[LL2]					
7	Augmented reality for professional applications	[LL2]				[LL2]	[LL1] [LL2]	[LL1]					
10	Position tracking of robots and UVs					[LL2]	[LL2]	[LL2]					
12	Virtual reality home gaming						[LL1]	[LL1]					

Table 2.8: Low latency requirements connecting use cases and KPIs in publications.

The main technical contributions are assigned to use cases and KPIs in Table 2.8.

- [LL1] contains publications [D3.4][D5.3][45][46] dealing with latencies in RW/D-MIMO implementations and a practical latency breakdown in commercial 802.11ad implementations.
- [LL2] contains publications [13][44][47] dealing with channel properties, user separability, and user rates for D-MIMO in industrial and laboratory environments.

2.5.2 Relation to infrastructure

From an infrastructure and systems perspective, channel measurements [13][47] confirm that there is significant channel hardening with distributed REs so that small-scale fading and large-scale fading are significantly decreased. This means that there should be a potential for ultra-reliable communication without coding over several packets and without retransmissions, in turn opening up for low-latency communication. The evaluation of the measurements in [44] indicates that there is a good potential for user separability, meaning that user orthogonality can be preserved and that multi-user interference can be limited. One should note, though, that more users mean less degrees of freedom for channel hardening. From an infrastructure perspective one should note that the number of co-processed signals from different REs need to be restricted, to limit the processing latency incurred by exchange of processing data inside and between CSPs. With fewer available REs to take part in transmission and reception of signals, everything else equal, follow higher packet loss probabilities.

2.5.3 Relation to devices

The critical use cases involve battery-powered, mobile end-user devices with significant energy-storage, computation, and communication capabilities (e.g., smartphones, VR goggles, etc.), with a potential for compute off-loading to the infrastructure if latency allows.

2.5.4 Algorithms

Packet sizes need to be restricted to allow enough time for processing to take place. With shorter packets, everything else equal, follow higher packet loss probabilities. An initial assessment, based on the time it takes to transmit a package, shows that packets of a few hundred bits or fewer may be required to meet the most demanding end-to-end latency requirements, such as for the *Real-time digital twins in manufacturing* use case.

> *There is significant channel hardening with distributed REs so that small-scale fading and large-scale fading are significantly decreased. This means that there should be a potential for ultra-reliable communication without coding over several packets and without retransmissions, in turn opening up for low-latency communication. The length of packets and distributed processing algorithms can constitute a limitation for low-latency communication in the system. An initial assessment, based on the time it takes to transmit a package, shows that packets of a few hundred bits or fewer may be required to meet the most demanding end-to-end latency requirements. The number of co-processed signals from different REs need to be restricted, to limit the processing latency incurred by exchange of processing data inside and between CSPs.*

2.6 Synchronization requirements

Synchronization requirements for a RW deployment are highly dependent on the use case and the dimensioned number of users. The requirements are different for communication and WPT use cases. The technical contributions and the advantages and limitations corresponding to synchronization are discussed in the subsequent parts of this section.

2.6.1 Main technical contributions

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
2	Real-time digital twins in manufacturing					[SR2]			[SR1] [SR2]				
5	Tracking of goods and real-time inventory					[SR2]	[SR1]		[SR1]				
6	Electronic labelling	[SR3]				[SR3]	[SR3]					[SR3]	
10	Position tracking of robots and UVs					[SR2]	[SR1]		[SR1]				
13	Smart home automation								[SR1]		[SR1] [SR2]		

Table 2.9: Synchronization requirements connecting use cases and KPIs in publications.

The main technical contributions are assigned to use cases and KPIs in Table 2.9. Publications and deliverables that are of importance for achieving or analyzing the synchronization requirements for use case-KPI combinations are grouped as follows.

- [SR1] contains synchronization and calibration aspects (such as clock and phase offset parameters) including the fundamental performance limits and algorithms with related publication [48] and deliverable [D3.3, Ch. 3] dealing with high reliability and positioning accuracy.
- [SR2] contains aspects corresponding to architectures for synchronization in the deliverables [D2.1, D2.2] dealing with deployment of RadioWeaves.
- [SR3] contains algorithms to synchronize a RadioWeave environment with related publications and deliverable [49, 50, 51, 52, 53, D3.2], [D3.3, Ch. 4] dealing with deployment in complex environments.

2.6.2 Relation to infrastructure

[D2.2, Ch. 2] discussed the different kinds of clock (CLK) sources and architectures which can be used to synchronize the CSPs in a distributed wireless communication system.

[D3.3, Ch. 3] analyzed the fundamental performance limits (Cramér-Rao lower bound (CRLB), position and synchronization error bounds) for joint positioning and synchronization for a RW system consisting of multiple CSPs in configurations consisting of multiple subarrays each. The main point of interest is the achievable performance for positioning for different system configurations, e.g., number of subarrays, number of array elements per subarray, number of CSPs, as well as the dependency on system parameters such as bandwidth. This provided valuable insights into the hardware requirements to achieve different levels of performance and allowed quantifying the losses due to system restrictions.

A RadioWeaves infrastructure with distributed antennas must be phase-calibrated (synchronized) for certain operations, such as reciprocity based joint coherent downlink beamforming, to work. In [48], we used rigorous signal processing tools to analyze the accuracy of calibration protocols that are based on over-the-air (OTA) measurements between antennas, with a focus on scalability aspects for large systems. We showed that (i) for some who-measures-on-whom topologies, the errors in the calibration process are unbounded when the network grows; and (ii) despite that conclusion, it is optimal – irrespective of the topology – to solve a single calibration problem for the entire system and use the result everywhere to support the beamforming. The analyses are exemplified by investigating specific distributed antenna topologies, including lines, rings, and two-dimensional surfaces.

2.6.2.1 Synchronization Requirements for WPT

In [41], we experimentally validated the required synchronization to perform WPT to an END through a distributed multi-antenna system. Fortunately, we demonstrate that a standard deviation of the phase error (with respect to perfect CSI) of up to 20 degrees, causes only a loss of up to $1\,\mathrm{dB}$.

> *Radioweaves has to be phase-calibrated as the network grows, however for WPT, a small phase error leads to a minor loss in performance.*

2.6.3 Relation to devices

Strategies to provide accurate synchronization depend on the device classes in [D1.1, Sec. 3.1]. The device classes indicate the capability of the devices to store energy or not. For instance, device classes 1 and 2 only perform backscatter communications with limited or zero power storage capabilities. Therefore, the synchronization requirements can be less stringent to transmit power wirelessly to them. On the other hand, certain classes of devices which can actively transmit signals while at the same time need WPT need stricter synchronization requirements with the environment for high beamforming gains and support high data rates.

> *Synchronization requirements for RadioWeaves is less stringent for WPT, whereas it may affect the devices which can actively transmit signals.*

2.6.4 Algorithms

2.6.4.1 Frequency and Phase Calibration with Beamsync Protocol

We developed Beamsync protocol, which is an OTA, carrier frequency and phase synchronization protocol for distributed multi-antenna CSPs in RadioWeaves infrastructure [49, 50, D3.2]. In BeamSync, we consider one of the CSPs as the primary CSP and others as secondary CSPs, which need to synchronize with the primary CSP. BeamSync removes the requirement of dedicated circuits for synchronization at transceiver nodes. Moreover, the scheme does not exchange calibration data through wired fronthaul connections and enables a faster carrier frequency synchronization. BeamSync exploits the diversity benefits of the multiple antennas at each CSP to beamform the synchronization signal. The primary CSP beamforms the frequency synchronization signal towards the secondary CSPs in the dominant direction of the channel between the primary and secondary CSPs. The secondary CSPs estimate their frequency offset with respect to primary using signal processing techniques. We showed that the optimal beamforming direction, which minimizes the offset estimation error, is the dominant direction of the channel between the CSPs in which the signal is received.

> *Synchronization signals have to be sent in the dominant direction to minimize the offset estimation error between the CSPs.*

2.6.4.2 Reciprocity Calibration in Distributed Massive MIMO for Coherent Operation

We studied reciprocity calibration of distributed massive MIMOs systems [51, D3.3]. In particular, we presented a model for the calibration setup, where a joint beam scanning procedure is executed by all CSPs of the network in order to collect measurements for calibration. We laid out the maximum likelihood cost function for the calibration problem at hand, and proposed a computationally-efficient alternating optimization procedure. We showed that the optimization procedure is guaranteed to converge. Via Monte-Carlo simulations, we verified the performance enhancements of the proposed method, compared to straightforward applications of state-of-the-art calibration schemes in the context of distributed massive MIMO systems.

> *A maximum-likelihood estimation of the calibration coefficients lead to an improved synchronization of the CSPs in the RadioWeaves infrastructure.*

2.6.4.3 Phase Calibration of Distributed Antenna Arrays

Antenna arrays can be either reciprocity calibrated (R-calibrated), which facilitates reciprocity-based beamforming, or fully calibrated (F-calibrated), which additionally facilitates transmission and reception in specific physical directions. We first exposed, to provide context, the fundamental principles of OTA R-and F-calibration of distributed arrays. We then described a new method for calibration of two arrays that are individually F-calibrated, such that the combined array becomes jointly F-calibrated [52].

> *A fully-calibrated RadioWeaves infrastructure facilitates transmission and reception in specific directions.*

2.6.4.4 Reciprocity Calibration of Dual-Antenna Repeaters

We developed a reciprocity calibration method for dual-antenna repeaters in wireless networks [53]. The method uses bi-directional measurements between two network nodes, A and B, where for each bi-directional measurement, the repeaters are configured in different states. The nodes A and B could be two access points (APs) in a distributed MIMO system, or they could be a base station and a mobile user terminal, for example. From the calibration measurements, the differences between the repeaters' forward and reverse gains are estimated. The repeaters are then (re-)configured to compensate for these differences such that the repeaters appear, transparently to the network, as reciprocal components of the propagation environment, enabling reciprocity-based beamforming in the network.

Even though REINDEER did not set out to investigate nodes with repeater-only functionalities, the work performed in REINDEER provided early insights on how repeaters with reciprocal properties have the potential to improve the propagation conditions, including channel rank, in a multi-user MIMO context.

2.6.4.5 Extended Kalman Filter based Position Tracking and Clock-synchronization

The extended Kalman filter-based algorithm from [D3.3, Section 4.3] investigated the application of [54] to the RW infrastructure as baseline algorithm for joint synchronization and positioning, which can be applied either to tracking of a dynamic UE or to measurement fusion of a static UE. For positioning, we exploit the LoS path in a similar fashion as in the analysis of the fundamental performance limits in [D3.3, Ch. 3], relying on a LoS-only model as simplest baseline case. While this will be a limitation that needs to be addressed during algorithm validation with measurement data, a simple pre-selection step from all measurements obtained per CSP, e.g., subarray, can be performed, e.g., using the algorithms obtained with the developed graph-based algorithm.

> *A pre-selection step from multiple measurements per CSP improves a limitation in the synchronization and positioning analysis of the LoS only model.*

2.7 Multiple access

2.7.1 Main technical contributions

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
2	Real-time digital twins in manufacturing					[MA2]			[MA2]			[MA1]	
5	Tracking of goods and real-time inventory					[MA2]			[MA1]			[MA1]	
6	Electronic labelling	[MA3]				[MA3]	[MA3]					[MA1]	
10	Position tracking of robots and UVs					[MA2]			[MA2]				
12	Virtual reality home gaming	[MA3]											
13	Smart home automation								[MA1]		[MA2]		

Table 2.10: Multiple access connecting use cases and KPIs in publications.

The main technical contributions are assigned to use cases and KPIs in Table 2.10. Publications and deliverables that are of importance for achieving or analyzing the multiple-access requirements for use case-KPI combinations are grouped as follows.

- [MA1] contains deliverable [D2.3] discussing about the multiple-access techniques for energy-neutral devices deployed in a RadioWeaves infrastructure.
- [MA2] contains publications related to deployment of user devices in complex environments focusing on high positioning accuracy.
- [MA3] contains publications and deliverables related to the multiple access of massive number of devices deployed in indoor and outdoor environments dealing with sporadic activity patterns [36, 55, 56, 57, 58, D3.2].

2.7.2 Relation to infrastructure

RadioWeaves brings the advantage of many transceivers on the fly. Multiple transmitters and receivers can be dynamically configure multiple-input single-output (MISO) configurations for multiple access [D2.3]. Collision avoidance protocols have to be incorporated in a RadioWeave infrastructure for multiple access. Directional antennas or phased array antennas can be incorporated in the infrastructure to read tags in specific spatial zones.

> *Coherent operation combined with directional and/or phased array antennas are essential to support multiple access for energy neutral devices deployed in the RadioWeaves infrastructure.*

2.7.3 Relation to devices

Deliverable [D2.3] discusses about spatially multiplexing multiple simultaneous backscattering devices with a RadioWeaves infrastructure. Collisions occur due to multiple energy neutral devices which have to be handled by techniques such as collision avoidance, beam isolation, etc.

Orthogonal multiple access (OMA) protocols have to be deployed and appropriate algorithms need to be implemented in the devices.

> *Collision avoidance mechanisms have to be incorporated so that different types of multiple access can be supported by the devices in the RadioWeaves infrastructure.*

2.7.4 Algorithms

2.7.4.1 New Distributed AMP Algorithm for Activity Detection in Grant-Free Multiple Access

We developed a new algorithm for user activity detection for grant-free multiple access in D-MIMO [55, D3.2]. The activity patterns of the UEs can be used to allocate time/frequency resources by the CSPs. The algorithm is a distributed version of the approximate message passing (AMP)-based on a soft combination of likelihood ratios computed independently at multiple CSPs. The underpinning theoretical basis of our algorithm is a new observation that we made about the state evolution in the AMP. Specifically, with a minimum mean square error (MMSE) denoiser, the state maintains a block-diagonal structure whenever the covariance matrices of the signals have such a structure. We showed by numerical examples that the algorithm outperforms competing schemes from the literature.

> *A likelihood ratio combination from multiple CSPs offers an improved activity detection performance in grant-free multiple access systems.*

2.7.4.2 Clustering-Based Activity Detection for Grant-Free Random Access in Distributed MIMO Systems

We investigated the activity detection in grant-free random-access (GFRA) for massive machine-typed communication (mMTC) in cell-free massive MIMO networks using distributed arrays. Each active device transmits a non-orthogonal pilot sequence to the CSPs and the CSPs send the received signals to a central-processing unit (CPU) for joint activity detection. The maximum likelihood device activity detection problem is formulated and algorithms for activity detection in cell-free massive MIMO are provided to solve it. The simulation results show that the macro diversity gain provided by the distributed array architecture improves the activity detection performance compared to co-located architecture when the coverage area is large [57, 36].

> *The macro diversity gain provided by distributed CSPs provide an improved activity detection performance of grant-free multiple access.*

2.7.4.3 Robust Covariance-Based Activity Detection for Massive Access

The wireless channel undergoes continuous changes, and the block-fading assumption, despite its popularity in theoretical contexts, never holds true in practical scenarios. This discrepancy is particularly critical for user activity detection in GFRA, where joint processing across multiple resource blocks is usually undesirable. In this contribution, we proposed employing a low-dimensional approximation of the channel to capture variations over time and frequency and robustify activity detection algorithms [56]. This approximation entails projecting channel fading vectors onto their principal directions to minimize the approximation order. Through numerical examples, we demonstrated a substantial performance improvement achieved by the resulting activity detection algorithm.

> *A low dimensional approximation of the channel using projection onto their principal directions robustify the activity detection performance in grant-free multiple access systems.*

2.7.4.4 A Flexible Framework for Grant-Free Random Access in Distributed MIMO Systems

We developed a novel generalized framework for GFRA in cell-free massive MIMO systems where multiple geographically separated CSPs aim to detect sporadically active UEs [58]. Unlike a conventional architecture in which all the active UEs transmit their signature or pilot sequences of equal length, we admit a flexible pilot length for each UE, which also enables a seamless integration into conventional grant-based wireless systems. We formulated the joint UE activity detection and the distributed channel estimation as a sparse support and signal recovery problem, and described a Bayesian learning procedure to solve it. We developed a scheme to fuse the posterior statistics of the latent variables inferred by each CSP to jointly detect the UEs' activities, and utilized them to further refine the channel estimates. In addition, we alluded to an interesting point which enables this flexible GFRA framework to encode the information bits from the active UEs. We numerically evaluated the normalized mean square error (NMSE) and the probability of miss-detection (MD) performances obtained by the Bayesian algorithm and show that the latent-variable fusion enhances the detection and the channel estimation performances by a large margin. We also benchmarked against a genie-aided algorithm which has a prior knowledge of the UEs' activities.

> *A posterior statistics fusion scheme improves the activity detection and channel estimation performance in variable length pilot based grant-free multiple access systems.*

2.8 Backhaul/fronthaul requirements

Backhaul (BH) and fronthaul (FH) requirements for a RW deployment are highly dependent on the use case and the dimensioned number of users. The backhaul capacity requirement, in broad terms, is determined by the peak sum data rate over all simultaneous users to be supported; the capacities of individual BH connections in the case of multiple BH feed points should generally sum to the same. For the total fronthaul capacity, as well as the capacity requirement in individual FH links in segmented deployment types, it is more difficult to provide generally applicable rules of thumb. These heavily depend on the adopted architecture. E.g. use of distributed processing and interference control can significantly ease the capacity and latency requirements for parts of the FH network.

2.8.1 Main technical contributions

Table 2.11 presents the main technical contributions addressing BH and FH aspects in relation to REINDEER use cases and KPIs:

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
1	Augmented reality for sports events		[BF2] [BF3]		[BF1]	[BF1]	[BF2] [BF3]	[BF1] [BF2] [BF3]					
2	Real-time digital twins in manufacturing		[BF2] [BF3]			[BF1]	[BF2] [BF3]	[BF1] [BF2] [BF3]					
5	Tracking of goods and real-time inventory				[BF1]	[BF2] [BF3]	[BF2] [BF3]						
7	Augmented reality for professional applications		[BF2] [BF3]		[BF1]	[BF1]							
12	Virtual reality home gaming		[BF2] [BF3]					[BF1]					

Table 2.11: Backhaul/fronthaul requirements connecting use cases and KPIs in publications.

- [BF1] contains publications describing fronthaul algorithms and backhaul connection strategies designed for RW deployments: [59]
- [BF2] contains publications describing distributed extensions to traditional UL/DL MIMO processing architectures that reduce the need for aggregate fronthaul capacity: [60] [61] [62] [63] [64]
- [BF3] contains publications describing new frameworks to enable decentralized MIMO receiver processing that reduce fronthaul capacity requirements: [65]

2.8.2 Relation to infrastructure

BH and FH capacity are key requirements for RW product development and deployment planning. In cases where a system is deployed to support primarily a specific use case, e.g., a specialized network for logistics tracking, the capacity requirements may derived from the use case itself, e.g., based on the projected peak data rates and the number of simultaneous active users/objects. In other scenarios, a network may be deployed as multi-purpose, supporting numerous simultaneous use cases. The BH and FH capacity requirements may then by dominated by the use case with the largest total data volume or the one with the highest instantaneous data rate. If multiple services with comparable capacity requirements are supported, the total requirement may be obtained as a sum of the individual use cases.

The BH functionality is generally supported by the distributed service federation (DSF) or federation anchor (FA) node(s) in the RW system architecture for all use cases. The BH functionality in REINDEER use cases is not expected to deviate significantly from BH provision in conventional network deployments.

The FH architectures and algorithms to support RW operation, on the other hand, are expected to differ from conventional solutions. In contrast to the traditional "star"-type connection patterns where each CSP has a dedicated link to the corresponding ECSP or DSF, the RW FH support is expected to be more segmented in nature. The lengths of the individual links are shorter, their typical data rates lower, and adjacent nodes have an opportunity to observe relevant parts of each others' data and weights, enabling distributed processing. The resulting HW will also be much more use case specific, where cost/performance-optimized HW for the segments may be achieved using wired or wireless FH links between the CSPs. The architecture also includes HW support for fast routing updates to support dynamic selection of co-scheduled user sets.

> *BH capacity considerations in RW operation do not differ significantly from traditional deployments for use cases with similar total data rate requirements. FH architures, on the other hand, may differ significantly and, depending on the use case, requiring segemented architectures and matching routing solutions.*

2.8.3 Relation to devices

The BH and FH requirements are primarily the function of the underlying use case(s), where the corresponding device functions and capabilities are implicitly already accounted for. We do thus not expect a direct relation of BH/FH requirements to device requirements. However, a deployment plan should account for a gradual increase of device capabilities over time, e.g. support of continually growing data rates in augmented reality and gaming use cases.

> *The BH and FH architectures are expected to be largely transparent to devices but the BH/FH system requirements need to scale depending on the anticipated number of devices and their service quality needs.*

2.8.4 Algorithms

2.8.4.1 Routing in segmented FH

The project has studied routing solutions that are suitable for RW operation with segmented FH. The segmented structure of neighbor-node connections between N CSPs with distributed processing results in 2·O(N) "short", reduced-rate and -cost inter-CSP connections instead of O(N) "long", high-rate ECSP-CSP links. As found in [59], an important bottleneck is created by points where the central nodes, required at least for BH provision, are connected to the FH distribution network; the segments near those locations may be deployed with higher capacity or multiple entry points from different RW edges may be used.

> *Segmented FH with efficient routing algorithms allows a significant reduction in FH network cost if data feed bottlenecks are avoided, e.g. by scaling up some segments or providing multiple feed points.*

2.8.4.2 Distributed processing to reduce FH requirements

Distributed processing is a key feature for allowing fronthaul data reduction in segmented or other architectures with inter-CSP connections and local compute resources. The project has therefore also studied multiple aspects of decentralized MIMO processing. Decentralized precoding weight computation and distribution for DL transmission [60] reduces the fronthaul load asociated with weight provision to individual CSPs. Decentralized subset combining of received UL symbols [61] [62] breaks the complex problem of symbol combining from a large number of CSPs into multiple smaller problems, obviating the need for transferring the very high volume of overall received symbol samples to a central location. This leads to a significantly reduced data bandwidth and latency requirements on the FH connection, where the reduction may be on the order of O(M), M being one the dimension of the segmented FH network.

In a sequential RW architecture, the uplink signal estimation is distributed and should happen sequentially and not in parallel. In such an architecture, the numerical stability of two different implementations of the recursive least squares algorithm is studied, considering that the fronthaul links connecting CSPs have limited capacity to exchange data between two CSPs [63].

Distributed processing also enables cooperative quantization of the received signal vector in the CSPs which is studied in this project. To be more specific, received data vectors at the CSPs are correlated to each other, assuming local channel knowledge. Hence, to efficiently use the quantization bits in a reference CSP, the received signal vector is de-correlated from the received signal vector of the preceding CSPs in the sequence and then quantized. This de-correlation is based on the exchanged data between the subsequent CSPs. The de-correlated vector elements have a smaller variance. Hence, the corresponding quantizer has a smaller dynamic range, which means that for a fixed number of bits, the quantization noise variance is less compared to the case where the received signal vector in each CSP is quantized in isolation from other CSPs. From another perspective, we can quantize the de-correlated vector with a low number of bits. As a consequence, the result of multiplication of the de-correlated vector with the combining matrix has a lower bit length, and hence the rate on the fronthaul link connecting the reference CSP to the next CSP in the processing pipeline [64].

> *In the RW architecture, it is often highly advantageous to replace centralized processing at a central node with distributed/decentralized processing in many nodes in a segmented RW FH network to determine precoding and combining weights across multiple nodes, as well as to combine received UL signals from multiple nodes. Methods for partitioning such computation problems and for ensuring high performance and stability of the resulting solutions were developed in the project.*

2.8.4.3 Over-the-Air Fronthaul Signaling for Uplink Cell-Free Massive MIMO Systems

We proposed a novel resource-efficient analog OTA computation framework to address the demanding requirements of the UL fronthaul between the APs and the CPU in cell-free massive MIMO systems [65]. We discussed the drawbacks of the wired and wireless fronthaul solutions, and showed that our proposed mechanism is efficient and scalable as the number of APs increases. We presented the transmit precoding and two-phase power assignment strategies at the APs to coherently combine the signals OTA in a spectrally efficient manner. We derived the statistics of the APs' locally available signals which enabled us to to obtain the analytical expressions for the Bayesian and classical estimators of the OTA combined signals. We empirically evaluated the NMSE, symbol-error rate (SER), and the coded bit error rate (BER) of our developed OTA framework and benchmarked against the state-of-the-art wired fronthaul based system.

> *A wireless FH solution was developed using OTA combining for FH functionality in a RW deployment, improving system performance compared to state of the art and admitting analytical expressions for important KPIs.*

2.9 Device mobility

According to the defined use cases [D1.1], the device mobility varies from $0\,\mathrm{m/s}$ (static) to $10\,\mathrm{m/s}$ (high mobility). Considering the selected center frequencies of $f_c = \{900\,\mathrm{MHz}, 2.4\,\mathrm{GHz}, 3.8\,\mathrm{GHz}, >5\,\mathrm{GHz}\}$, the maximum Doppler shift is $166.6\,\mathrm{Hz}$ according to the formula $f_{d,\mathsf{max}} = (vf_c)/c$, where v, f_c and c are the device velocity, the central frequency and the speed of light, respectively. This Doppler shift translates into a channel coherence time of $3\,\mathrm{ms}$ based on the definition $T_{\mathsf{coh}} = 1/(2f_{d,\mathsf{max}})$.

In a MIMO system, the base station requires estimating the channel in UL and using it for the DL precoding. However, a channel coherence time of $3\,\mathrm{ms}$ means that the CSI gets outdated rapidly. And using outdated CSI leads to losing beamforming gain completely. To deal with that, the REINDEER team in [D3.4, Ch. 2] explores using the knowledge of historical CSI to improve the beamforming gain by predicting the future location of the UE. However, if the position of the UE is unknown, we proceed by deducing the possible future locations using an unknown mapping from the CSI space to the physical domain. In the same deliverable, the REINDEER team studies a solution to jointly estimate delay and the Doppler shift and track the user position over time, which can be used for the precoding solution mentioned before. In [66, Sec. 5.4], we go a step further and demonstrate on realistic real-world data that we are able to estimate the user position and environment geometry using realistic real-life channels. We are able to predict the user position multiple time steps to the future and even predict CSI multiple time steps ahead at the cost of only a marginal efficiency loss. We are capable of doing so both in LoS and even in OLoS conditions, exploiting NLoS paths via walls previously learned using our algorithm. Our method drastically outperforms measured CSI which is outdated by only a single time-step which underlines the severe advantages of channel estimation and prediction for efficient and resilient communication and power transfer under user mobility.

In addition, orthogonal frequency-division multiplexing (OFDM)-based waveforms deal well with multipath propagation environments, however, they exhibit a detrimental performance under high mobility cases due to their sensitivity to high Doppler shift. As an alternative, in [D3.4, Ch. 2] as well, we propose an FM-OFDM (frequency-modulated OFDM) waveform that can improve the overall BER system performance while reducing the peak-to-average power ratio (PAPR).

Finally, selecting appropriate mobility models is crucial for accurately simulating these use cases in wireless network environments. In [D3.4, Ch. 1], we select suitable mobility models for each use case category depending on each requirement.

2.9.1 Main technical contributions

The main technical contributions are gathered to use cases and KPIs in Table 2.12. Publications and deliverables that are connected to device mobility for use-case-KPI combinations are shown as follows:

- [DM1]. This group deals with issues that arise from high mobility [D3.4, Ch. 2], and [40].
- [DM2]. This group estimates the Doppler shift for sensing and/or positioning purposes [D3.4, Ch. 3], [56], and [67].
- [DM3]. It makes efficient use of the infrastructure by taking benefit from the device mobility [D3.2, Ch. 5], and [68].

	KPIs → use cases ↓	Massive number of devices/connections A	High traffic volume/sum rate B	High peak rate C	Higher mobility speeds (up to 7-10 m/s) D	Deployment in open or complex environments E	High reliability F	Low latency G	High positioning accuracy H	Low-energy communication I	Low-energy positioning J	Energy-neutral devices and WPT K	Real-time processing, edge computing support L
2	Real-time digital twins in manufacturing				[DM1]		[DM1]	[DM1]	[DM2]				
5	Tracking of goods and real-time inventory				[DM3]		[DM3]	[DM3]	[DM3]				
7	Augmented reality for professional applications				[DM1]		[DM1]	[DM1]					
10	Position tracking of robots and UVs				[DM1]		[DM1]	[DM1]	[DM2]				
12	Virtual reality home gaming				[DM1]		[DM1]	[DM1]	[DM2]				

Table 2.12: Device mobility connecting use cases and KPIs in publications.

2.9.2 Relation to infrastructure

In [D3.2, Ch. 5], we introduce the concept of *federation*, a group of serving resources and served UEs. The serving resources can include communication resources, i.e., CSPs, wireless power transfer resources, positioning services, edge computing capabilities, data storage services, or any other resources provided by the RadioWeaves infrastructure and needed by the application. In addition, the federation anchor is responsible for the operation of the federation. This may include such functions as scheduling of radio resources (e.g., time or frequency resources) for the users of the federation, communicating with other federation anchors to negotiate resource allocation, signalling between the infrastructure and the served applications, and admission control of UEs to the federation.

This infrastructure allows to dynamically move serving resources in terms of the user circumstances which indeed copes well with high mobility settings. For instance, one of the biggest challenges is mobility in the UV tracking use case. To account for the UV's mobility, the federation is adapted as the UV moves. Some CSPs are not currently serving the UV but are standing by to join the federation as it is predicted the UV will move in their direction. This dynamic adaptation of the federation as it "follows" the robot around the factory floor ensures a consistently good channel even as the robot passes objects that may cause shadowing, while also allowing the federation's panels to be physically close to each other to provide low latency communications.

2.9.3 Relation to devices

The device classes 1 and 2 are energy-neutral devices that only backscatter the signal in the UL. Hence, these devices are usually static and they do not impose any mobility challenge.

However, classes 3 and 4 are empowered devices such as robots and UVs, and are used for use cases with high mobility settings. As described in the introduction, high mobility results in a very short channel coherence time, which must be handled with robust precoding solutions. However, as shown earlier, a system can take advantage of mobility because we can predict where the device will be to arrange resources in advance so that the reliability is significantly improved.

2.9.4 Algorithms

The nature of RW allows distributed processing and dynamical arrangement of radio resources. Therefore, the federation needs to be updated according to the user's position. In [D3.2, Ch. 5], we have discussed an algorithm for that purpose but the convergence is not guaranteed. Guaranteed convergence is however not required if full re-allocation is available as a fallback mechanism in case a dynamic update fails.

In addition, the distributed system can be used to obtain not only user information but also situational awareness of the environment. To this end, in [D3.4, Ch. 3] we explore a delay-Doppler estimation solution based on Bayesian inference algorithms.

Our holistic channel estimation, -prediciton, and -fusion algorithm from [66, Sec. 5.4] demonstrates that positioning and environment learning can be leveraged to predict future CSI even in the case of high device mobility. We outperform outdated measured CSI already by a large margin when predicting CSI a single time step into the future, although we are capable of predictions multiple time steps ahead at little efficiency cost. Our channel fusion method provides a probabilistic combination of a noisy measured channel and a geometry-base predicted channel subject to position uncertainty. While coming at the cost of some efficiency, it can provide further robustness in case one of the two types of CSI fails to provide a reliable performance.

> *High device mobility introduces Doppler shifts and causes a low channel coherence time.*
>
> *Predicting CSI based on position can be done in a data-driven approach.*
>
> *We show that our holistic model-based approach is capable of jointly estimation the environment geometry, device position, and device motion (i.e., velocity) which it uses to predict CSI to future time steps, leading to resilient and efficient geometry-based beamforming.*

Chapter 3

Summary and Limitations

In Section 2.1, we have shown that a RadioWeaves infrastructure inherently provides robust **positioning** through its distributed nature. We have also demonstrated on realistic channel measurements, that environment learning can be used for robust positioning, leveraging non-line-of-sight (NLoS) propagation to bypass obstructed line-of-sight (OLoS) conditions. Our developed algorithms account for non-stationarity effects in distributed infrastructures, user mobility, and harsh multipath environments with possible obstructions, where we demonstrate centimeter-level positioning accuracy through theoretical performance bounds and real-world channel measurements.

Discussing the **operation of energy neutral (EN) devices** in Section 2.2, we have shown that a physically large, or distributed radio infrastructure such as RadioWeaves can achieve high receive powers in the milliwatt level when operating at sub-10 GHz frequencies. Acquiring channel state information (CSI) is vital for beamforming, which imposes the initial-access problem before the operation of batteryless EN devices and further necessitates ultra-robust beamforming to avoid the device entering a region of a deep fade during operation. Our algorithms prove that positioning and environment learning can be used in holistic algorithms to estimate and predict CSI for geometry-based beamforming which outperforms conventional reciprocity-based beamforming in low SNR regimes, improving efficiency and robustness. To fully leverage their capabilities, more flexible algorithms capable of dealing with the probabilistic estimation and tracking of high-dimensional geometric state spaces need to be developed in future research. The most challenging electronic shelf label (ESL) use case powered via radio frequency (RF) wireless power transfer (WPT) was thoroughly explored, and its feasibility was demonstrated. Various techniques to power energy neutral devices (ENDs) were simulated and practically tested in different testbeds, such as reciprocity-based and geometry-based distributed beamforming. Signal designs were generated, and the harvester's efficiency and response time during initial access were evaluated.

In Section 2.3, we have explored several **initial access** and beamforming schemes that are CSI-free and some that work with geometry-based, predicted CSI. The former has proven to be more effective for the wake-up of massive numbers of devices and does not rely on a phase calibration as the latter. The choice of initial access scheme to use ultimately depends on the number of devices to wake up, the device side power requirements, and the synchronization level at the infrastructure side.

In Section 2.4, we address the **peak** and **aggregate data rates**. In terms of individual-user experienced peak data rates, the *Augmented Reality for Professional Applications* use case has the highest requirement with 45 Mbps for compressed video and up to 3 Gbps for uncompressed video. Simulations and measurements indicate that it should be possible to support those challenging use cases with reasonable user densities and bandwidths. As expected, it is, however, a challenge to support extreme data rates as in the case of uncompressed video for many simultaneous users without increasing the number of antennas at the device side. For the *Augmented reality for sport events* use case the number of Radio Units have to be scaled up significantly to be on par with the number of spectators.

To supply the needs of the defined use cases, we discussed the **low latency** and **reliability** requirements of a RadioWeaves infrastructure in Section 2.5. There is significant channel hardening with distributed radio elements (REs) so that small-scale fading and large-scale fading are significantly decreased. This means that there should be a potential for ultra-reliable communication without coding over several packets and without retransmissions, in turn opening up for low-latency communication. The length of packets and distributed processing algorithms can constitute a limitation for low-latency communication in the system. An initial assessment, based on the time it takes to transmit a package, shows that packets of a few hundred bits or fewer may be required to meet the most demanding end-to-end latency requirements. The number of co-processed signals from different REs need to be restricted, to limit the processing latency incurred by the exchange of processing data inside and between contact service points (CSPs).

In Section 2.6, we address the tight **synchronization requirements** that a distributed RadioWeave architecture faces w.r.t. to the clock error models of distributed clocks. Possible over-the-air (OTA) synchronization and calibration algorithms have been proposed, fundamental performance limits established, and theoretical scaling properties of distributed network synchronization addressed. We have shown that imperfections in calibration will affect the CSI leveraged for beamforming and result in losses.

In Section 2.7, we have discussed a multitude of **multiple access** schemes that can be supported by and designed for a distributed RadioWeaves infrastructure-based system. Several grant-free multiple-access schemes have been proposed and their advantages and limitations discussed. Collision avoidance schemes that need to be supported for multiple access in energy-neutral devices have been mentioned. The macro diversity and multiplexing gains provided by distributed antennas improve multi-user multiple access performance exemplified by activity detection and channel estimation for grant-free massive random access schemes.

In Section 2.8, we discuss the **backhaul/fronthaul requirements** which, while transparent to the users, need to scale depending on the anticipated number of users. We formulated a segmented fronthaul (FH) solution with an efficient routing algorithm that allows a significant reduction in FH network cost. Distributed algorithms for precoding and combing have been developed for the RadioWeaves (RW) architecture that allow moving processing from a central location out to individual nodes in the network, reducing FH capacity requirements. Related contributions include methods for partitioning such computation problems and for ensuring high performance and stability of the resulting solutions. We also developed a FH solution using OTA combining, which improves system performance over state-of-the-art methods.

We address **device mobility** in Section 2.9, finding that high-mobility settings impose some challenges, particularly the fact that the CSI data gets outdated quickly. To deal with that, a combination of solutions from new beamforming techniques to a new orthogonal frequency-division multiplexing (OFDM) waveform have been proposed. On the other hand, we have shown that a system can exploit the device motion model to estimate its trajectory, predict its future position and either arrange resources in advance to minimize outages or even predict CSI entirely using a geometry-based channel model.

Deliverables

[D1.1] M. Truskaller,, and J. F. Esteban, “Use case-driven specifications and technical requirements and initial channel model,” REINDEER project, Deliverable ICT-52-2020, Mar. 2023. DOI: 10.5281/zenodo.5561844

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[D2.1] O. Edfors, “Initial assessment of architectures and hardware resources for a RadioWeaves infrastructure,” REINDEER project, Deliverable ICT-52-2020, Jan. 2022. DOI: 10.5281/zenodo.5938909

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[D3.1] S. Rimalapudi, “Analytical Performance Metrics and Physical-Layer Solutions,” REINDEER project, Deliverable ICT-52-2020, Jan. 2022. DOI: 10.5281/zenodo.5938647

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