Accepted for presentation in: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Istanbul, Türkiye, Sep. 2025

Improving Energy Efficiency of Industrial mmWave Connectivity with Context-Sensitive IRS Support

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***Abstract*—The advancement of wireless communication technologies, especially in the context of Millimeter-Wave (mmWave) frequencies, is facilitating novel advancements in industrial applications. This study investigates the energy efficiency of mobile mmWave end devices deployed within industrial settings. Utilizing and extending an established laboratory setup, an experimental framework is developed to create device-specific energy profiles and conduct precise mobility testing. Measurements based on robotic evaluation scenarios are performed to analyze the interplay between energy consumption and performance under varying radio conditions caused by mobility, alignment, and Line-of-Sight (LOS) availability. The findings highlight improvement opportunities by optimizing end device orientation and incorporating additional network hardware to minimize Non-LOS (NLOS) conditions via Beyond-LOS (BLOS) links, which in turn enhance the overall energy efficiency. The optimization techniques implemented lead to a notable stabilization of the end device's throughput alongside a 19.9 % decrease in power consumption resulting in a 29.1 % higher energy efficiency. These results are crucial for extending the operational duration of mobile applications while minimizing charging needs and offer significant insights for future research aimed at advancing mmWave-enabled devices for industrial robotics.**

***Index Terms*—mmWave communications, energy efficiency, mobility, LOS/NLOS, reflecting surfaces.**

I. Introduction

The rapid evolution of wireless communication technologies has introduced new paradigms for industrial applications, particularly with the advent of Millimeter-Wave (mmWave) frequencies. Operating in Frequency Range 2 (FR2), mmWave technology offers significant benefits such as enhanced data rates and improved capacity, making it an attractive option for modern industrial environments to connect their mobile robots via the network to enable wireless and autonomous operation. Previous studies have predominantly concentrated on exploring the performance potentials of FR2, highlighting capabilities such as ultra-high throughput, low latency, and massive connectivity—demonstrated through various experimental setups and simulations. However, there remains a critical gap in literature regarding the energy efficiency of mmWave-enabled end devices as well as the overall network. Nonetheless, as 6G aims to support ubiquitous connectivity and AI-driven applications, optimizing energy consumption is crucial for sustainability and cost efficiency. Therefore, energy efficiency indicators are becoming increasingly important and should therefore be taken into account at every stage, from initial research to pre-development and eventual network deployment, as the authors in [1] stated.

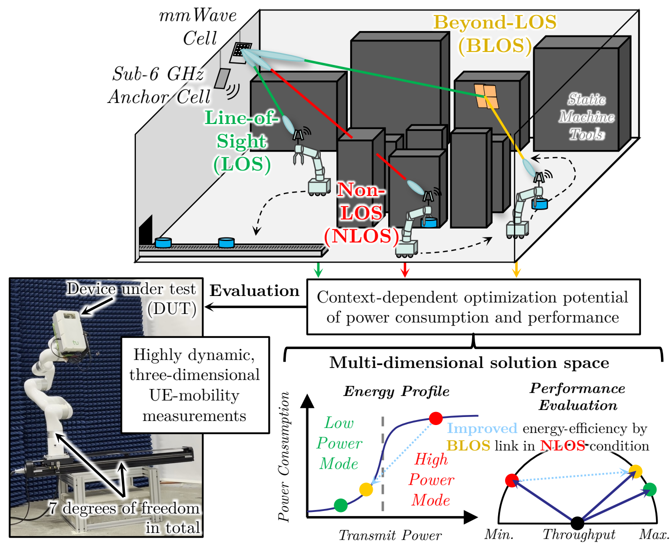


Fig. 1: Context-dependent optimization potential for mmWave-enabled mobile industry applications evaluated by robot-assisted measurements.

In this paper, we present a comprehensive study on energy profiling and performance trade-offs of mmWave end devices used in mobile industrial applications. Building upon established laboratory setups previously utilized for sub-6 GHz measurements, this experimental framework is adapted to facilitate accurate mmWave testing and develop device-specific energy profiles. To utilize our findings in a real-world context, we transfer the derived profiles to an industrial environment equipped with a commercial mmWave network. Through the implementation of robotic evaluation scenarios, reproducible end device trajectories are conducted to evaluate the interplay between energy consumption and performance under varying conditions such as mobility, alignments, and Line-of-Sight (LOS) availability. The results aim to provide valuable insights into optimizing mmWave end devices for industrial applications while balancing their energy efficiency with operational performance.

In Fig. 1, an industrial scenario is outlined in which mobile robots move through an industrial indoor environment while autonomously performing production applications. They are connected to a mmWave network, via which large amounts of data can be transmitted to monitor the processes and teleoperate the autonomous machines in case of anomalies. Due to the end devices' mobility, variable radio conditions occur within the environment, which affects both their energy consumption and performance. This creates the potential to optimize the trade-off between the two metrics through improved orientation of the end devices as well as the introduction of additional network hardware, creating Beyond Line-of-Sight (BLOS) links. These mitigation strategies aim to minimize Non-Line-of-Sight (NLOS) conditions by providing improved connectivity between the Base Station (BS) and mobile users, which is particularly crucial for battery-powered devices to enhance energy efficiency and extend operating time before battery depletion.

The remainder of this work is structured as follows. In Sec. II, further research on energy efficiency in FR2 and other improvements to increase energy savings are discussed. This is followed by the methodology in Sec. III, which is used to derive energy profiles and develop reproducible evaluation scenarios. The results obtained are subsequently analyzed in Sec. IV and optimization strategies evaluated. Finally, the findings of this work are summarized and an outlook for further research activities is given.

II. Improvements in Energy Efficiency of FR2

It is anticipated, as described in [2], that the power usage within the information and communication technology sector will continue to rise in the following years. As a result, energy-saving measures are becoming increasingly important to minimize the emissions and operational costs of current and future networks. This makes energy efficiency improvements for all network components a key issue, particularly with regard to 6G. In addition to this work, several other studies are focusing on optimizing the trade-off between performance and power consumption in mobile networks, as the following examples show.

In [3], a comprehensive measurement campaign was conducted within commercial networks featuring various system and context parameters. The results indicate that mmWave frequencies can significantly enhance energy efficiency in bandwidth-hungry applications while highlighting that using Frequency Range 1 (FR1) is more efficient for less demanding applications. One challenge noted during these experiments is that energy measurements in mobility experiments are not trivial. This issue can be addressed by employing an energy profile derived from the procedure presented in this study.

Similarly, the authors in [4] investigate the power consumption of mmWave-enabled (60 GHz) end devices as well, but for Wireless Fidelity (Wi-Fi) technology. The detailed analysis reveals how beamforming and searching impact the energy consumption of end devices—a finding highly relevant for mobile devices operating in FR2, as explored in this work—and underscores the necessity for ongoing enhancements of these processes.

As stated in [5], operators also aim to achieve energy savings on the network side to reduce operational expenses. Within this report, concepts are discussed aiming at energy savings without affecting coverage, capacity and Quality of Service (QoS). To evaluate the energy efficiency, mobile network metrics from [6] are utilized—metrics that hold relevance for this study as well. Accordingly, energy efficiency (EE) can be determined from the data volume (DV) and the energy consumption (EC) as follows:

$$EE\,[\text{bit/joule}] = \frac{DV\,[\text{bit/s}]}{EC\,[\text{joule/s}]} \tag{1}$$

The approach of improving energy efficiency within a mmWave network using intelligent reflectors is not only pursued in this paper but also in numerous others, such as [7], [8], [9] and [10]. The focus on industrial applications in many of these cases stresses the relevance of mmWave connectivity, which can serve as an enabler of autonomous robotic processes. For this reason, the application of FR2 must be further tested and improved, such as through the strategies discussed in this paper.

The laboratory setup for measuring power consumption has been extended based on preliminary work outlined in [11], which concentrated on the sub-6 GHz range. This extension facilitates measurements for FR2 networks as well. Although similar system parameters contribute to high energy demand across both frequency ranges, it is notable that current mmWave-enabled User Equipments (UEs) have a significantly higher consumption than those operating within FR1. Nonetheless, evaluating the energy efficiency of mmWave requires considering the comparatively high performance achievable with this technology. Therefore, mobility tests are incorporated into this study to assess both performance and power consumption effectively.

III. Methodology for Energy Profiling and Optimization of Reproducible Mobility Tests

In this chapter, the methodology of this work is explained in two steps. First, the laboratory setup is described, with which the power consumption of end devices is examined in order to derive a corresponding energy profile. In the second step, highly dynamic, three-dimensional mobility tests are established, which are utilized in combination with the energy profile to evaluate and validate various optimization strategies with regard to energy efficiency.

A. Development of Device-Specific Energy Profiles

In Fig. 2, the laboratory setup and the linking of components are outlined, that are utilized to analyze the energy consumption of a Device Under Test (DUT) for different emulated mobile networks. A central control unit is deployed to initiate the automated process and collect the resulting data during all measurements. At first, a configuration is transferred to the network emulator, which processes the settings and adjusts the connected sub-6 GHz and mmWave antennas within the shielding box accordingly. The DUT is also located inside the chamber to minimize external interference during measurements. At the beginning of each measurement series, the network is configured to signal the end device to transmit at maximum power via closed-loop power control. During an active data transmission initiated by *iperf* [12], the power consumption is recorded using a power supply and meter which powers

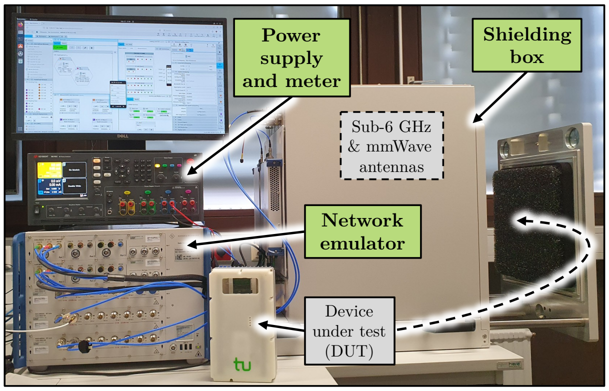


Fig. 2: Laboratory equipment for context-sensitive energy measurements.

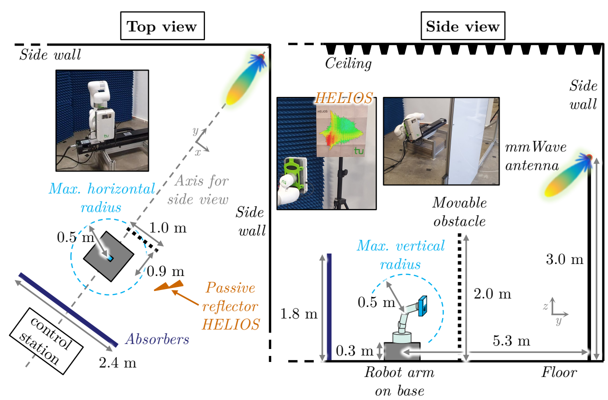
the DUT inside the chamber while the power metrics are transmitted to the central control unit. This process is repeated five times for each network configuration and UE transmission power level to filter out possible measurement inaccuracies. In the next step, the network configuration is retained, but the signaled transmission power of the end device is gradually reduced. The previously described procedure is repeated for one network configuration until the measurements have been carried out for all possible transmission power levels of a UE.

Conducting such a series of measurements for various configurations of the network allows to determine which system parameters have the strongest influence on the power consumption of an end device and can therefore be optimized. In contrast, the mobility tests explained next are utilized to investigate the impact of context parameters on energy efficiency and performance of mobile users.

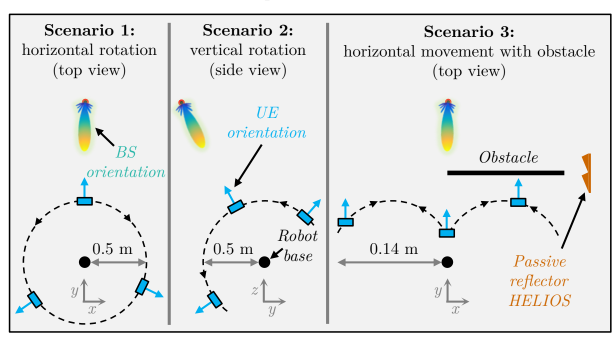
B. Reproducible Mobility Testing and Optimization Strategies

Robot-assisted tests are conducted within a small-scale industrial hall, with the layout sketched in Fig. 3a. To minimize the influence of the control station, absorbers are placed between it and the robot arm. Apart from this, the propagation of radio waves within this highly metallic environment is not restricted, so several propagation paths can arise between UE and BS. After evaluating the baseline performance of the mobile end device in three initial scenarios (cf. Fig. 3b), changes to the context parameters are analyzed to optimize the trade-off between power consumption and performance of the end device. For this purpose, a passive Intelligent Reflecting Surface (IRS) is deployed within the environment to improve connectivity in challenging radio conditions by creating a BLOS link between the BS and mobile UE. Therefore, a Holistic Enlightening of bLackspots with passIve reflectOr moduleS (HELIOS) reflector [13] is utilized, which has a total size of $40\,\mathrm{cm} \times 40\,\mathrm{cm}$ using a custom-designed 4×4 module arrangement, which results in a broadened vertical reflection beam with 17.8° beam width. In addition, in a second optimization step it is investigated how an adjustment of the UE orientation increases its energy efficiency. This allows the maximum antenna gain of the DUT to be utilized, for example by aligning the main beam direction with that of the BS or, in case of NLOS conditions, by aiming it at a suitable reflective surface to improve connectivity.

The mobility tests are based on initial scenarios whose trajectories are designed to investigate the effect of the UE's orientation towards the BS and to challenge its beamforming through the implementation of variable radio conditions, for example by introducing obstacles. As shown in Fig. 3b, a distinction is made between three scenarios. During horizontal rotation, the DUT at the end of the outstretched robot arm is rotated around the Z-axis at a constant distance from the ground, with the main beam direction of its mmWave antenna elements permanently pointing away from the axis of rotation. In comparison, in scenario 2 (vertical rotation) only the axis of rotation changes from Z to Y. In the third scenario, an obstacle in the form of a metallic plate is placed as indicated to interrupt the LOS between the end device and BS halfway along the trajectory. Each measurement series of a scenario involves traversing through its trajectory five times. Meanwhile, the key performance indicators (KPIs) of the end device and the commercial mmWave network are recorded while an active data transmission is carried out. For the latter, the maximum Uplink (UL) data rate is queried via *iperf* [12] using User Datagram Protocol (UDP) to ensure a high load on the UE. Combined with the recorded end device position provided by the programmable robot arm, the metrics are plotted for evaluation in two- and three-dimensional space. The configuration of the deployed DUT and mmWave network are described in detail in Tab. I.



(a) Measurement setup within small-scale industrial hall



(b) Scenarios for analysis of mobility impact on mmWave connectivity

Fig. 3: Concept of measurement setup and reproducible mobility tests.

TABLE I: Configuration of the DUT and NSA mmWave mobile network.

	Parameter	Description/Value
User Equipment	Device Model	Quectel 5GDM01EK with Quectel RG530F-EU
	Modem	Qualcomm SDX65
	mmWave Antenna Module	RA530T with four QTM547 (8×8, cross-polarized)
	LTE Category	Cat 20 / Cat 18 (DL/UL)
	5G NR Compliance	Release 16 NSA/SA
	Power Class	Class 3 (23 dBm)
	MIMO Capabilities	FR1: DL 4×4, UL 2×2 FR2: DL 2×2, UL 2×2
Cell Configuration	**FR1 / LTE Anchor Cell**	
	Radio Unit	Ericsson Radio 2203
	Frequency Band	LTE band 7 (FDD)
	Center Frequency	2.65 and 2.53 GHz (DL/UL)
	Bandwidth	20 MHz
	Transmit Power	100 mW (EIRP)
	FR2 / NR mmWave Cell	
	Radio Unit	Ericsson AIR 1281
	Frequency Band	5G NR n257 (TDD)
	Frequency Range	26.7 to 27.5 GHz
	TDD Pattern	DDSU
	TDD Special Slot Pattern	11:3:0
	Component Carriers (CCs)	1 (of up to 8)
	Bandwidth	100 MHz per CC
	Subcarrier Spacing (SCS)	120 kHz
	Transmit Power	100 mW (EIRP)

In order to validate the impact of the mobility scenarios developed, ray-tracing simulations using *Wireless InSite* [14] were carried out in a realistic model of the industrial hall, which, in addition to the antenna characteristics of the BS and the UE, also include the material properties of the deployed objects. The simulation results confirm that the connectivity is strongly influenced by the implemented UE orientation and mobility as well as the positioned obstacle, resulting in varying radio conditions that influence the power consumption of the DUT. Thus, the above-mentioned optimization strategies can be evaluated by comparing the improvements in performance and reduction in UE transmit power with the initial scenarios.

IV. Evaluating Efficiency Optimization Strategies

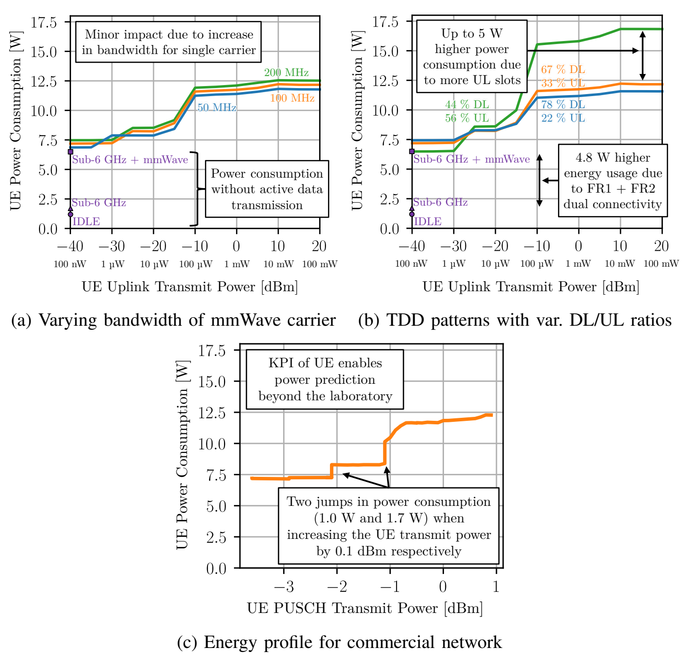
In this section, the results of the measurements carried out are evaluated in three steps. First, the impact of system parameters on the energy consumption of a DUT is discussed based on the results obtained utilizing the laboratory setup. Next, the effect of variable context parameters is analyzed based on the mobility tests conducted. Finally, these results are used to validate the effectiveness of different optimization strategies based on the measured and estimated KPIs.

A. Network Configuration's Impact on UE Power Usage

Using the laboratory equipment described above, one of the following parameters of the mmWave cell is varied for each series of measurements: frequency, Modulation and Coding Scheme (MCS), bandwidth, and Time Division Duplex (TDD) pattern. While different carrier frequencies between 26.75 GHz and 27.45 GHz as well as MCS indices between 2 and 28 showed no significant effect on the power consumption of the connected DUT, the results of three different bandwidths and TDD patterns are shown in Fig. 4a and Fig. 4b. Thereby, the UL transmit power of the UE is indicated on the X-axis and the corresponding power consumption on the Y-axis.

Firstly, it is striking that the power consumption of the UE increases significantly when dual-connected with the sub-6 GHz and mmWave cell (6.49 W). In contrast, the consumption in IDLE state is 1.20 W, and with a single connection to the sub-6 GHz cell 1.68 W. If the bandwidth of the mmWave carrier is now set to 50 MHz, 100 MHz and 200 MHz during active data transmission, there is a steady, although small, linear increase in UE power consumption. However, the behavior is different when varying the TDD pattern. These results show that a higher proportion of slots used for transmission in UL direction leads to up to 5 W higher energy consumption. These findings match those of [11] for mobile devices in FR1, although the maximum energy consumption of the mmWave UE investigated in this work is up to 15 W higher.

To estimate the power consumption of the UE as accurately as possible during mobility tests, the same network configuration listed in Tab. I is set in the network emulator for corresponding power measurements. A device-specific energy profile, which is shown in Fig. 4c, is derived so that the power consumption measurement results can be used to estimate the energy consumption of the device in mobile applications outside the laboratory. The UE power consumption is shown over the Physical Uplink Shared Channel (PUSCH) transmit power of the DUT. The latter KPI can be queried directly from the UE and is therefore well suited for power consumption estimation if no energy meter is available. The progression of the energy profile shows that the power consumption of the UE increases abruptly twice. These nonlinear jumps can be caused by power amplifiers and other hardware components installed within the device and may therefore vary for different DUTs.



(a) Varying bandwidth of mmWave carrier (b) TDD patterns with var. DL/UL ratios

(c) Energy profile for commercial network

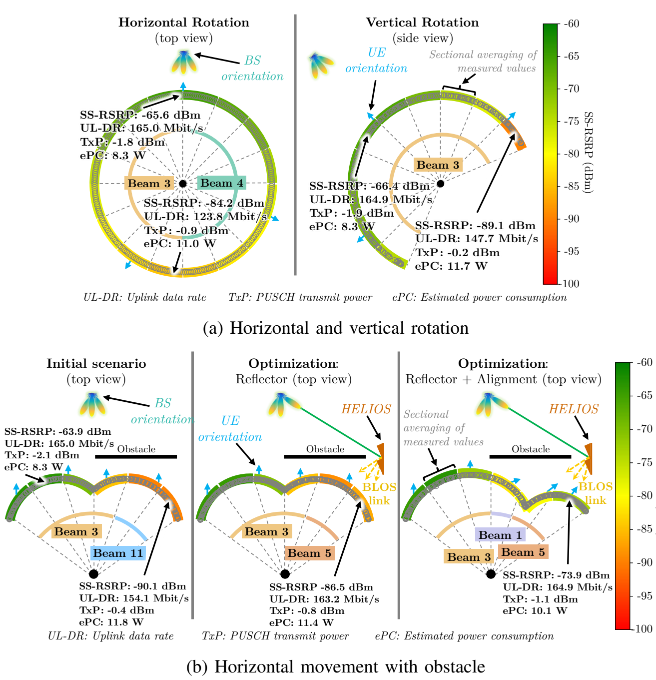
Fig. 4: Impact of system parameters on UE power consumption and derived energy profile for deployed network during mobility tests.

B. Effect of Mobility on mmWave Connectivity

To investigate the influence of mobility on mmWave connectivity and simultaneously on the UE's performance and power consumption, the measurement results of the previously defined trajectories are evaluated and displayed in Fig. 5a for horizontal and vertical rotation. Although the perspective differs in both illustrations (top and side view), the evaluation is the same: the trajectories are divided into 22.5° circular sections and the recorded KPIs are evaluated on average within these. The connectivity in the form of Synchronization Signal Reference Signal Received Power (SS-RSRP) is colored according to the value for each section of the trajectory. Also plotted for each section is the mmWave cell's beam index, which is used to connect to the UE. The values of the UL data rate (UL-DR), the UE PUSCH transmit power (TxP) and the resulting estimated power consumption (ePC) are shown for selected sections, but can also be evaluated for every section.

In both scenarios, as expected, connectivity, performance, and power consumption are best when the UE is in LOS and aligned with the mmWave BS. If the device is rotated in other directions using the robot arm, the listed metrics deteriorate. For example, for the horizontal rotation, the SS-RSRP decreases by up to 18.6 dB, and the throughput in UL direction by 41.2 Mbit/s, while the PUSCH transmit power increases by 0.9 dB, which leads to a 2.7 W higher power consumption from the end device based on the energy profile shown in Fig. 4c.

The deterioration of the measured KPIs in NLOS areas is similar during the vertical rotation scenario, although the decrease in connectivity can be compensated for better with a higher transmission power of the end device and the use of reflection paths, e.g. via the ceiling, so that the measured



(a) Horizontal and vertical rotation

(b) Horizontal movement with obstacle

Fig. 5: Evaluation of the initial mobility tests as well as optimization strategies.

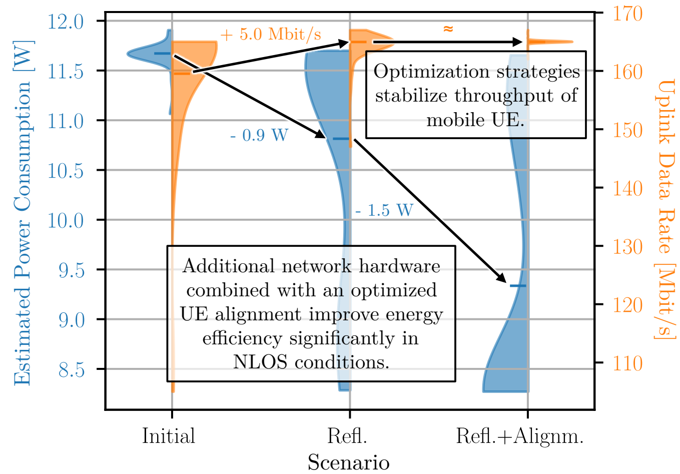


Fig. 6: Distribution of values of estimated power consumption and UL throughput in NLOS area during horizontal movement.

data rate only falls to 147.7 Mbit/s. However, the automatic transmit power adjustment of the UE simultaneously results in an increased power consumption of 11.7 W.

C. IRS-based Optimization for Improved Energy Efficiency

To validate two optimization strategies, the scenario of horizontal movement with obstacle is examined in more detail in Fig. 5b. In the initial scenario, the influence of the obstacle becomes apparent: while the SS-RSRP, UL data rate, PUSCH transmit power, and estimated power consumption in LOS average −63.9 dBm, 165 Mbit/s, −2.1 dBm and 8.3 W respectively, the values in the NLOS area behind the obstacle deteriorate to −90.1 dBm, 154.1 Mbit/s, −0.4 dBm and 11.8 W. The comparatively high data rate behind the obstacle is possible due to multipath propagation within the industrial radio environment. Due to the predominantly metallic objects, constructive reflection paths can occur, which enable connectivity between BS and UE. Nevertheless, in contrast to LOS, the considerably lower receive power and higher transmit power at the UE are noticeable.

To counteract the degraded connectivity and high energy consumption of the UE in NLOS, a first optimization measure is to place the HELIOS reflector in the radio environment so that it is located in LOS of both the BS and the UE. The orientation of the IRS is adjusted so that the received power at the end device is maximized. With an unchanged UE alignment, the received power behind the obstacle increases by 3.6 dB and the throughput by 9.1 Mbit/s. The transmit power of the end device is reduced by 0.4 dB, which means an energy saving of only 0.4 W. Monitoring the beam indices shows that the BS now uses beam 5 instead of 11 to reach the end device in the NLOS range, confirming that the BLOS link is utilized. To further improve the energy efficiency of the UE, its alignment is optimized in the next step so that the mmWave antenna elements are oriented towards the reflector as soon as the LOS to the BS is interrupted. While the data rate is already close to the maximum value after the first optimization, the connectivity and power consumption are significantly improved by the adjusted alignment: compared to the initial scenario, the received power increases to −73.9 dBm while the transmit power and estimated power consumption decrease to −1.1 dBm and 10.1 W respectively.

A more detailed analysis of the estimated power consumption and the UL throughput in the NLOS area of the horizontal movement is shown in Fig. 6. The value distribution highlights that the deployment of the reflector and resulting BLOS link stabilizes the throughput, as the data rate at most measurement points is above 160 Mbit/s. Simultaneously, the UE transmit power drops on average by 0.9 W, caused by the improved connectivity, resulting in 10.9 % higher energy efficiency as per Eq. (1). Furthermore, the optimized alignment by pointing the UE towards HELIOS stabilizes the performance even more and reduces the estimated power consumption by 1.5 W, leading to an improvement of energy efficiency by 29.1 % compared to the initial scenario.

This mayor enhancement in energy efficiency, enabled by the context-dependent optimization strategies employed, is significant for the use of mobile devices. For example, in the context of industrial applications that are operated and controlled via mmWave-enabled devices, longer operating times and lower operational costs are possible compared to a non-optimized radio environment and UE alignment.

V. Conclusions and Outlook

In this study, a framework has been developed for evaluating and subsequently optimizing the performance and power consumption of mobile mmWave UEs by minimizing NLOS conditions in mobile applications, thus improving the overall energy efficiency. In this context, a controlled laboratory environment was first used to analyze the impact of various system parameters of a network on the power consumption of a DUT by utilizing a network emulator, shielding box and power meter. The resulting device- and network-specific energy profile was then applied to estimate the power consumption of this device accurately during mobility tests in conjunction with a commercial mmWave system. For these measurements, three initial scenarios were developed, with the help of which the influence of UE mobility and orientation on connectivity, performance and its energy consumption can be reproducibly tested. Two strategies were then evaluated to optimize the energy efficiency of an end device: Improving the connectivity by deploying a passive IRS to provide a BLOS link, as well as refining the alignment of the UE.

It is demonstrated by these outcomes that minimizing suboptimal connectivity has a significant impact on the performance and power consumption of mobile devices. The optimization strategies employed for the evaluated device led to a stabilized UL throughput and a reduction in power consumption, resulting in a device-specific energy efficiency improvement of 29.1 %. These enhancement potentials are relevant for future research and the deployment of mobile devices in any industrial application in order to increase their energy efficiency and battery life, thus enabling long-term utilization with minimal recharging time. Furthermore, incorporating hardware-level insights may offer a deeper understanding of the causes behind energy fluctuations and support the development of more targeted, energy-aware system optimizations for mmWave-enabled devices.

The presented methodology for devising device-specific energy profiles, as well as the developed mobility tests, will be conducted in the future on other hardware configurations such as newly released mmWave-enabled UEs to assess not only their performance, but also their energy efficiency and capability for mobile use cases. Furthermore, network planning algorithms are being developed to automatically determine the placement of passive IRSs, thereby translating empirical insights into actionable system-level design improvements that enhance the overall efficiency of mmWave networks. Additional approaches include comparison with alternative optimization techniques to benchmark efficacy, as well as the introduction of analytical models or predictive equations to enable simulation-driven evaluations and performance estimation. It is only through the consideration of these factors that the devices can be systematically improved in order to promote the use of FR2 in various industrial applications.

Acknowledgment

This work has been funded by the German Federal Ministry of Research, Technology and Space (BMFTR) in the course of the *6G-ANNA* project under grant no. 16KISK101 and the *6GEM Research Hub* under the grant no. 16KISK038 as well as by the Ministry of Economic Affairs, Industry, Climate Action, and Energy of the State of North Rhine-Westphalia (MWIKE NRW) along with the *Competence Center 5G.NRW* under grant no. 005-01903-0047.

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