SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Operations, Maintenance, and Component Reliability

https://doi.org/10.52825/solarpaces.v2i.858

Published: 24 Jul. 2024

5G as Communication Platform for Solar Tower Plants

5G for CSP

Peter Schwarzbözl[1], Inga Miadowicz[1], Daniel Maldonado Quinto[1], Julian Golembiewski[2], Pascal Jörke[3], Timm Faulwasser[2], and Christian Wietfeld[3]

[1] German Aerospace Center, Institute of Solar Research, Germany

[2] TU Dortmund University, Institute for Energy Systems, Energy Efficiency and Energy Economics, Germany

[3] TU Dortmund University, Communication Networks Institute, Germany

Abstract. Wiring of heliostat fields for solar tower plants is a cost factor that becomes more important as the overall cost target is decreasing. Wireless heliostats with radio communication and autarchic energy supply have therefore been proposed in the past. But none of the communication solutions investigated so far could realistically scale to commercial size plants with tens of thousands of heliostats. Moreover, the digitalization of CSP plants with numerous mobile and stationary sensor systems requires a suitable data communication, too. The new generation of mobile radio communication (5G) is capable of handling the heterogenous communication profile portfolio comprising large numbers of units with low data rates – like heliostats - and few units with very large data volume – like e.g. drone-based camera systems. The communication requirements of a typical solar tower installation are assessed in this work and a data traffic model is created for the most relevant communication channels. The various existing 5G implementations are assessed to find the most suitable solution. Different operator models for 5G are considered and their applicability in CSP target countries is discussed. A simulation test case is presented that models the radio communication traffic of a heliostat field control during a cloud passage. Finally, the experimental 5G campus network is introduced that is currently installed at the Solar Tower Jülich research plant and will be operated in the upcoming months to demonstrate the technical feasibility of 5G radio for communication in solar fields.

Keywords: Wireless Communication, Cable Free Heliostat Field, Autonomous Heliostats, 5G Radio Communication

1. Introduction

The effort and cost of CSP installations must decrease so that this renewable energy technology will be used more widely. The heliostat field accounts for about one third to one half of the total investment cost. A certain proportion of this is spent on cabling the heliostat field for communication and electrical power. In a 2011 study from SANDIA [1] the estimated cost for cabling ranges from 4.6% to 7.6% of the total field investment cost. This cost varies with heliostat size, the absolute amount per unit reflective surface area ranging from 8 US$$_{2010}$/m² to 18 US$$_{2010}$/m². This is in good agreement with [2], where specific cabling cost of about 11 US$$_{2002}$/m² are reported. Having in mind, that the cost goal for the collector field today is 75 US$/m² and below ([3]), it is obvious that cabling cost is also an issue. On the other hand, these figures show the benchmark for alternative solutions as wireless communication combined with PV/Battery power supply.

But cost is not the only motivation to look for alternatives to cabling of large area distributed systems in usually remote dessert-like areas. Past plant projects have shown that the least possible impact on nature is very important for social acceptance. On the other side, digitization in general and the application of modern – often mobile – sensor systems in particular is expected to increase the overall performance of CSP plants: drone-based measurement and detection systems, unmanned mirror cleaning vehicles, mobile maintenance operators, etc. These innovations mostly need wireless communication.

Therefore, several approaches have been made in the past to study radio-based communication for the control of heliostat fields ([2], [4], [5], [6]). These works focus on unlicensed ISM radio band solutions, like Wi-Fi or ZigBee and they verify the general functional principle. However, the necessary scalability for an extremely high number and density of participants associated with a heliostat field of several tens of thousands of units remains unsolved with these technologies. This work investigates the usage of the new generation of mobile radio networks (5G) as communication platform for solar tower systems.

2. Communication requirements of solar tower plants

The main routes of communication between the centralized control units and the distributed subsystems in the heliostat field are the scope of this work, as depicted in Figure 1. The communication requirements of a typical solar tower installation have been assessed and a data traffic model has been created for the most relevant communication channels. It describes each type of interface, the number of participants, exchanged messages and rates, priority and data volume (Table 1).

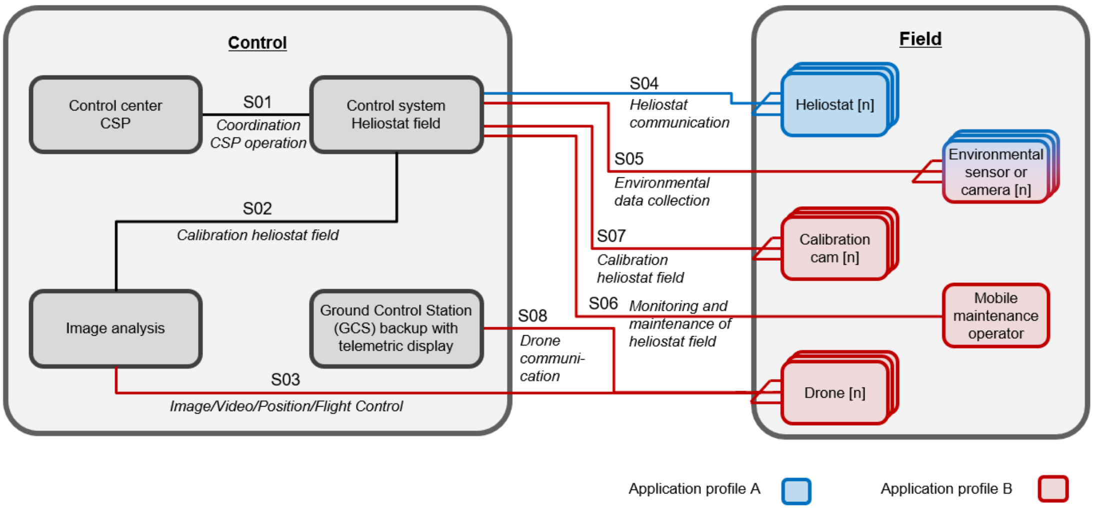

***Figure 1**. Main routes of heliostat field related communication in a solar tower plant.*

To limit the communication requirements – at least for larger heliostat fields - heliostats are assumed to be equipped with sufficient “intelligence” on their local controllers enabling them to track the sun and reflect its radiation to a given aim point autonomously. Accordingly, the central heliostat field control has to send commands only in case of aim point switches or changes of the operational state (e.g. going from on-sun track to standby). This reduces the communication rate drastically from once every few seconds to once every several minutes and longer.

It remains the problem what happens if the signal is lost. To detect this issue, heartbeat- and status-messages have to be exchanged between central unit and heliostat. If the signal is lost, a heliostat will autonomously move to a save off-receiver position. This permanent exchange of extremely small-volume messages causes a base load of communication in the network. The exchange rate depends on the heliostat field, the receiver requirements and the network capacity.

Table 1. *Description of the most relevant communication channels in a heliostat field.*

Interface	Description	Rate	No of units	Priority	Volume
S04	heartbeat (down) / status message (up)	> 1 /s	60.000	high	~10 Byte
	change mode (down) / new aimpoint (down)	< 0.1 /s	< 60.000	high	~50 Byte
S05	meteo sensors (up)	~1 /s	few	low	~50 Byte
	cloud camera (up)	~1 /s	1…6	medium	~0.3 MB
S07	single hi-res calibration image (up)	< 0.1 /s	1…4	low	~6.5 MB
	camera stream 4K (up)	24 fps	1…4	low	64 kB
S06	get heliostat field status (down)	~1 /s	few	low	~5 kB
	control singe heliostat (up)	~1 /s	few	low	~0.5 kB
S08	get position data (up) / flight control (down)	~10-20 /s	few	high	~0.25 kB
S03	video stream FHD (up)	24 fps	few	low	28 kB

According to their communication requirements the subsystems can be distinguished into two main profiles. Application profile A is characterized by a large number of participants with a rather low data traffic load but higher reliability requirement. The heliostats obviously belong to profile A. Typical heliostat fields of todays commercial tower plants comprise several thousand up to 60.000 items in a density varying from roughly 500 to 30.000 units per km². Other members of profile A can be distributed environmental data sensors (e.g. wind, temperature, brightness) or sensors connected to heliostats (e.g. inclination, vibration, cleanliness). Their number can also be high but data transfer priority and reliability is usually lower than for heliostat control.

Application profile B is characterized by applications with a usually smaller number of items but rather high data volumes. Typical representatives are cameras, e.g. for sky imaging, calibration, IR receiver monitoring or general surveillance. Also, mobile operators in the field with hand held data devices for maintenance. Finally, drones and drone-based cameras or other sensor systems for airborne measurements and surveillance.

A replacement of all wired communication channels between the distributed subsystems in the field and the central control with wireless communication is a big challenge, especially due to the highly heterogeneous requirements profiles.

Network participants of profile A transmit and receive system-critical but small amounts of data with an extremely high participant density. As the number of participants is high the wireless solution should be at low costs. Moreover, their energy consumption should be kept as low as possible, to allow realization of completely wireless heliostats powered by small PV-battery systems. Other communication channels can be characterized with a low number of participants but with very high data rates in each case (application profile B). Although this group of participants is relatively small, it is important that high resolution videos, images and other data can be transmitted with high reliability and low latency to allow data-based operation like real-time monitoring or automatic drone-control. This is seen as essential to open up the potential of digitizing the heliostat field with fully networked components.

3. 5G solutions for large area industrial applications

The 5G mobile radio technology is designed for a very heterogeneous requirement profile of enhanced mobile broadband, massive and critical machine type communication. It provides solutions for massive node density and reliability simultaneously. Moreover, it is deemed to provide sufficient capacity to meet the heterogeneous communication profile that comes with parallel control and monitoring applications [7].

In the use case of CSP, the monitoring and control of large heliostat fields requires reliable communication for tens of thousands of heliostats, which can only be provided by a centrally coordinated communication network such as cellular networks, which reduce message collisions to a minimum and therefore reliability to a maximum. Simultaneously, CSP-related applications like video and image-based heliostat calibration, either static or using UAVs, along with video surveillance, introduce further requirements of reliable broadband communication. Figure 2 gives an overview of the heterogeneous application requirements mapped on the different 5G capabilities and solutions. With large bandwidths for high data rates and optimizations for small data transmissions ([8], [9], [10]), 5G including 5G New Radio (5G NR) and Narrowband IoT (NB-IoT) is identified as suitable solutions for wireless communication in heterogeneous environments like CSP. Additionally, with 3GPP Release 17, 5G device categories are extended to an additional category, called 5G NR Reduced Capabilities (5G NR RedCap), which enables relaxed capabilities of the devices by reducing the bill-of-material costs by about 65%, while still providing data rates up to 150 Mbit/s in DL direction and 50 Mbit/s in UL direction [11], which makes it a cost-efficient, yet capable solution.

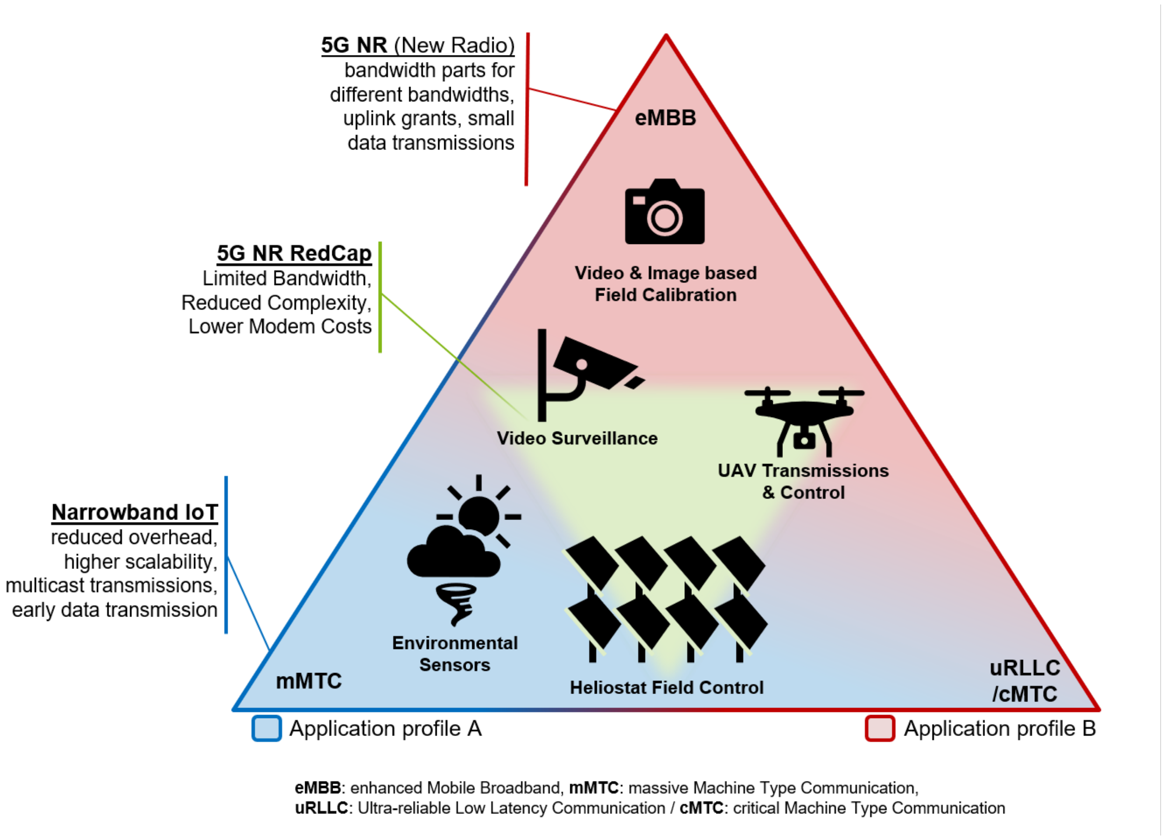

Figure 2. *Heterogeneous CSP applications mapped on different capabilities of 5G networks*

The objective of this work is to evaluate 5G solutions as a communication network in solar power towers from a technical and economical point of view. Additionally, the regulatory perspective of 5G solutions in relevant countries for CSP deployment will be evaluated.

Therefore, for a flexible deployment, different operator models for 5G can be considered:

1. Private network (campus network): Exclusive spectrum for ensured Quality of Service (QoS) and demand-driven network configuration. Base stations can be installed based on local requirements but require a license for spectrum usage.
2. Mobile network operator (MNO) based local solution: Using public 5G networks for good availability of spectrum and existing network infrastructure. The resources are shared between different users, which limits the QoS.
3. Virtual network via MNO-based network slicing: Public, licensed spectrum with network slices for ensured QoS.
4. 5G deployment in unlicensed spectrum: Globally available spectrum for an easy rollout of 5G deployment in various countries. The performance is affected by Listen Before Talk and Adaptive Frequency Agility techniques along with unknown numbers of other operators using the same frequency band.

For the CSP use case private 5G networks in licensed and unlicensed frequency bands provide a suitable solution for high communicative utilization with many systems and a long-term operation. For operating a private 5G network in licensed frequency bands, regulators must provide such spectrum for these networks. Currently, broadband spectrum for private 5G networks has already become available in Germany [12], Spain [13] and the USA [14], whose usage must be requested at administering agencies. In China a different approach for private 5G networks is used, since private networks are deployed Chinese MNOs, but then can be used exclusively [15].

Since the allocation of spectrum for local networks is still under development in many countries, private 5G deployments in license-free spectrum are a promising alternative. Since most CSP are deployed in rural areas, substantial interferences with other networks using the same frequencies are considered unlikely. With ISM bands for 2.4 GHz, 5 GHz or 6 GHz being available in CSP-relevant countries like USA, China, Morocco, Israel, Chile and Spain [16], missing availability of licensed spectrum for private 5G networks can be compensated by license-free deployments.

4. Heliostat field control communication

The impact of cloud passages is considered as one of the most critical situations when controlling a solar tower plant (see e.g. [17]). It shall serve as a benchmark for wireless control communication.

A reference plant of commercial size, which was used earlier by several other authors (e.g. [18]), is considered. It is a 450 MW_{th} molten salt power plant with cylindrical receiver and surround field. The heliostat field consists of 6482 units of 121 m² reflecting area each (Figure 3, right). A map of allowable flux density is applied to limit the radiation flux on the receiver surface. The heliostat field is subdivided into 350 groups as described by Oberkirsch et al. 2021 ([19]). All heliostats of one group aim at the same aim point on the receiver surface. For optimization purposes a fixed aim point grid with 470 aim points and two off-receiver aim points is employed (Figure 3, left).

The heliostats are assumed to have a local controller that is capable of self-tracking for a specified aim point, i.e. a sun position algorithm and a heliostat kinematic model allow the on-board calculation of the required motor movements. This is considered mandatory to reduce the number of required central control messages drastically. Accordingly, each group of heliostats receives messages from the central heliostat field control only in case of aim point changes or changes of operating mode (e.g. stop tracking, standby, emergency). It is estimated that when operating under constant load during clear sky conditions the aim point of one group has to be changed in the order of once very 10 minutes or less.

During cloud passage, it is assumed that an aim point optimization and control method is used to adjust the allocation of heliostat groups to aim points, with the goal of maximizing the intercepted power while maintaining the allowable flux density distribution. Aim point changes are restricted to a certain neighborhood to avoid excessive movements (Figure 3, left). For simulation of cloud passage over the reference plant the model setup described by Oberkirsch et al. 2023 ([20]) is used. A GPU-based static optimal control method is used which is fed by DNI nowcasting data to control cloud passages (see [20] for details). The control step interval is set to 10 sec, allowing 5 sec for optimization and 2.5 sec for moving the heliostats. Accordingly, every 10 sec a multicast of control messages is communicated to a certain number of heliostat groups that have to change their aim point.

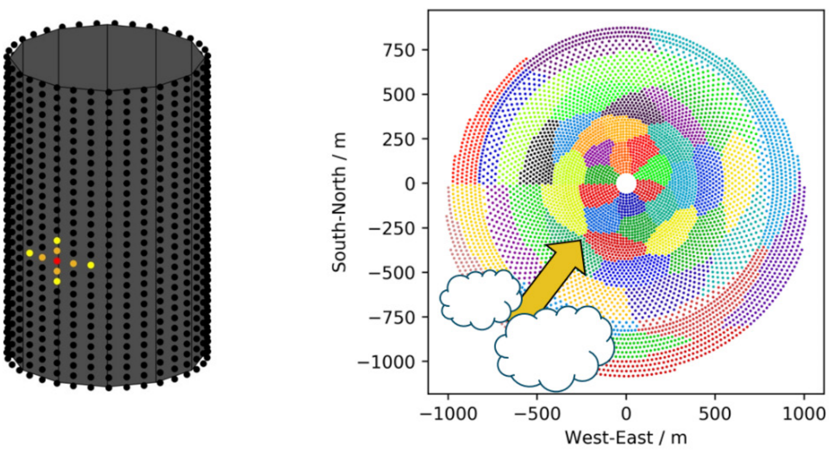

Figure 3. *Left: Aim point grid on receiver surface and allowed aim point change during one control step. Right: Cloud passage over reference heliostat field.*

The increased demand of control signals has the potential to overload the mobile network, leading to congestion issues that could significantly degrade plant performance [21]. To mitigate these challenges new methods capable of ensuring safe operation while maximizing the efficient utilization of network resources are of tremendous interest.

We propose a resource-based scheduling approach that dynamically adapts plant operations and leverages the flexibilities of the different communication channels that arise from the established priorities assigned to each message type. Interfaces with high priority play a crucial role in ensuring the safety and reliability of the system.

To proactively manage the communication load, the future demands can be predicted based on cloud forecast data. The predicted communication demand is subsequently utilized to relieve the mobile network by e.g. adjusting video quality from 4K to HD or SD, or by selectively delaying and discarding low-priority messages. The decision of whether a packet should be delayed or dropped depends on the predefined flexibility parameters within the data traffic model.

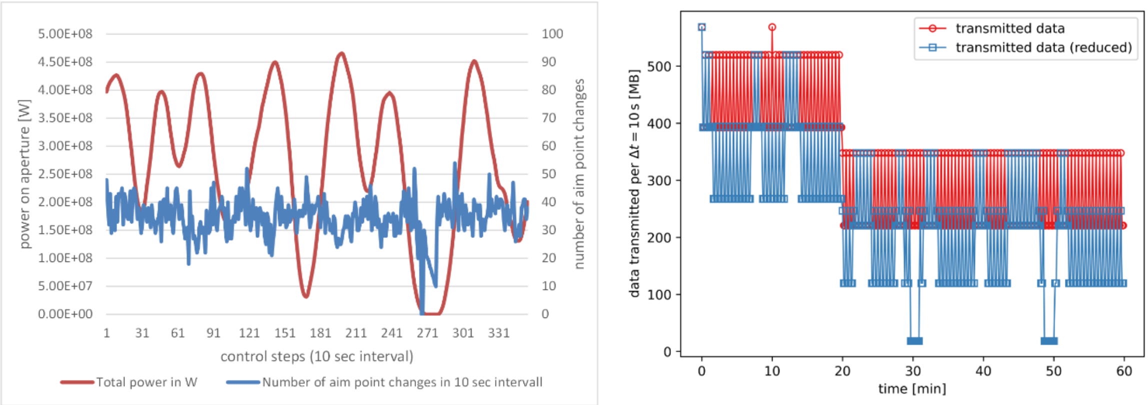

Figure 4. *Preliminary results of one hour of cloud passage simulation. Left: intercepted power on receiver aperture and necessary aim point changes for each control step. Right: transmitted data via the radio network with (blue) and without (red) usage of message scheduling.*

Figure 4 shows preliminary results from one hour of simulation. The left graph shows the intercepted power on the aperture that varies drastically due to the cloud passage over the reference heliostat field. The required rate of aim point changes during this extreme period is about 40 per 10 sec of control interval. The right graph shows the communication data load with and without application of message scheduling. As depicted, the proposed algorithm significantly reduces the amount of transmitted data over various periods. Depending on the prevailing cloud coverage and speed, actions were taken on an increasing number of interfaces while considering their respective priorities.

The communication load management prioritizes the transmission of new set points over low-priority messages. This prioritization strategy helps to maintain the mobile network congestion-free, prevents losses and delays, and contributes to the overall smooth operation of the plant.

5. Experimental 5G campus network at the Solar Tower Jülich

An experimental 5G campus network with licensed locally exclusive spectrum of 3.7 – 3.8 GHz is installed at the Solar Tower Jülich research plant. Core and baseband unit configure a 5G New Radio network which is wire-connected to the central heliostat field control. Two radio units and antennas are installed in the heliostat field for wireless connection of selected components that represent the range of most typical use cases:

- 10 not self-tracking (“dumb”) heliostats distributed over the field; two of these will additionally become energetically self-sufficient by equipping with PV-battery supply
- one heliostat which is equipped with self-tracking capability based on an industrial Raspberry Pi controller
- one weather station
- one calibration camera
- one mobile maintenance operator equipped with a tablet
- one drone and camera system, where both the flight control and the camera stream shall be performed via 5G radio communication

Besides demonstration of these use cases the assessment of communication performance data is foreseen. The test cases comprise:

- comparison of wireless and wired data communication in terms of data load, reliability and latency

- comparison of radio communication of self-tracking and not self-tracking heliostats at different operation modes
- assessment of radio communication quality depending on location relative to antennas

At the current time (October 2023) the 5G campus network is installed and operational. The use cases are successively equipped with 5G radio capabilities and connected to the network. First tests and demonstrations are imminent. An intensive live test period is planned for several months in 2024.

Data availability statement

Not applicable.

Author contributions

Peter Schwarzbözl: conceptualization, funding acquisition, methodology, supervision, writing

Inga Miadowicz: investigation, methodology, writing

Daniel Maldonado Quinto: conceptualization, supervision, visualization, review
Julian Golembiewski: conceptualization, investigation, software, writing
Pascal Jörke: conceptualization, investigation, writing
Timm Faulwasser: conceptualization, funding acquisition, resources, supervision, review
Christian Wietfeld: conceptualization, funding acquisition, resources, supervision, review

Competing interests

The authors declare that they have no competing interests.

Funding

This work is funded by the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia, Germany, under contract number 005-2108-0068.

References

1. SANDIA Report: Power Tower Technology Roadmap and Cost Reduction Plan (2011), SAND2011-2419
2. Romero, M., Egea, A., Gázquez, J. A., & García, G. (2002). Implementing wireless communication into heliostat fields. In Proceedings of the 11th Solar-PACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies (pp. 567-574)
3. Pfahl, A. et al., Progress in heliostat development, Solar Energy 152, 2017
4. García, G. et al. "Performance evaluation of the first solar tower operating with autonomous heliostats: PCHA project." Proceedings of the 12th SolarPACES Conference, Oaxaca, Mexico, 2004
5. Kubisch, S. et al. „Wireless heliostat and control system for large self-powered heliostat fields. In: Proceedings of the 12th SolarPACES Conference, Granada, Spain, 2011
6. Liebenberg, A.D. "Performance Evaluation of Wireless Communication in a Modular Heliostat Field", Thesis, Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, South Africa, 2021

7. 3GPP, “5G; Service requirements for the 5G system (3GPP TS 22.261 version 17.11.0 Release 15),” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 22.261, 2022, version 17.11.0.
8. P. Jörke, T. Gebauer, C. Wietfeld, "From LENA to LENA-NB: Implementation and Performance Evaluation of NB-IoT and Early Data Transmission in ns-3", In Work-shop on ns-3 (WNS3), Online, June 2022
9. P. Jörke, T. Gebauer, S. Böcker, C. Wietfeld, "Scaling Dense NB-IoT Networks to the Max: Performance Benefits of Early Data Transmission", In 2022 IEEE 95th Vehicular Technology Conference: VTC2022-Spring, Helsinki, Finland, June 2022.
10. P. Jörke, D. Ronschka, C. Wietfeld, "Performance Evaluation of Random Access for Small Data Transmissions in Highly Dense Public and Private NB-IoT Networks", In 2023 IEEE 97th Vehicular Technology Conference (VTC-Spring), Florence, Italy, June 2023.
11. Ericsson, "RedCap - expanding the 5G device ecosystem for consumers and industries", White Paper, February 2023
12. BNetzA, Frequenzzuteilungen für lokale Frequenznutzungen im Frequenzbereich 3.700-3.800 MHz, 01.12.2021. Link: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Frequenzen/OffentlicheNetze/LokaleNetze/Verwaltungsvorschrift3.7-3.8GHz_pdf.pdf?__blob=publicationFile&v=5
13. European Utilities Telecoms Council, Response to the request to the request from Spanish Ministry of Economic Affairs and Digital Transformation for comments on the recently issued frequency allocation table (CNAF), May 2021. Link: https://eutc.org/media/2021/07/2021-05-EUTC-Response-to-Spanish-National-Framework-of-Attribution-of-Frequencies-ES-EN-1.pdf
14. FCC, Online Table of Frequency Allocations, 01.07.2022. Link: https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf
15. Nick Beckett and Kelly Chen and Yili Liao, "5G Regulation and Law in China", CMS Legal Services EEIG, 2023. Link: https://cms.law/en/int/expert-guides/cms-expert-guide-to-5g-regulation-and-law/china
16. WiFi Alliance, "Countries Enabling Wi-Fi in 6 GHz". Link: https://www.wi-fi.org/countries-enabling-wi-fi-in-6-ghz-wi-fi-6e
17. G. Augsburger und D. Favrat, „Modelling of the receiver transient flux distribution due to cloud passages on a solar tower thermal power plant“, Solar Energy, Bd. 87, S. 42–52, 2013
18. R. Flesch, C. Frantz, D. Maldonado Quinto, P. Schwarzbözl, Towards an optimal aiming for molten salt power towers, Solar Energy 155 (2017) 1273 – 1281.
19. Oberkirsch, L., Maldonado Quinto, D., Schwarzbözl, P. and Hoffschmidt, B. (2021) GPU-based Aim Point Optimization for Solar Tower Power Plants. Solar Energy. Elsevier. doi: 10.1016/j.solener.2020.11.053
20. Oberkirsch, L., Zanger, D., Maldonado Quinto, D., Schwarzbözl, P. and Hoffschmidt, B. (2023) Static optimal control: Real-time optimization within closed-loop aim point control for solar power towers. Solar Energy, 255, Elsevier. doi: 10.1016/j.solener.2023.03.051
21. G. A. Akpakwu, B. J. Silva, G. P. Hancke and A. M. Abu-Mahfouz, "A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges," in IEEE Access, vol. 6, pp. 3619-3647, 2018