Lens antenna adjustment for telecommunication and imaging modes in a sub-THz radio system

Ali Ghavidel1 | Sami Myllymäki1 | Mikko Kokkonen1 | Nuutti Tervo2 | Heli Jantunen1

1Microelectronics Research Unit, University of Oulu, Oulu, Finland
2Centre for Wireless Communications, University of Oulu, Oulu, Finland

Correspondence
Ali Ghavidel, Microelectronics Research Unit, University of Oulu, P.O. Box 4500, FI-90014 Oulu, Finland.
Email: ali.ghavidel@oulu.fi

Funding information
Academy of Finland 6Genesis Flagship, Grant/Award Number: 318927

Abstract

This article presents a concept of a dual-mode operated sub-THz frequency radio system by adjusting the lens-antenna distance for either telecommunication or imaging modes. The signal transmittance and imaging capabilities are demonstrated using a continuous wave operated transceiver with operation frequency 220 to 330 GHz where the 6G wireless radio system could be allocated. A high-gain bullet-shape lens antenna was investigated for imaging the natural object (Bergenia leaf) in the short-range line-of-sight radio link. The bullet lens performed with the gain of 28 dB and the 1° beamwidth over the frequency band. For the demonstration of dual-mode operation, the leaf was placed into the middle of the radio link path and then its image was synthesized at three lenses to the antenna-distances by utilizing the inverse synthetic-aperture radar technique. For image synthesizing, the movement pattern area (100 mm × 100 mm) is defined with 5 mm steps to sweep the object area. Three 100 mm × 100 mm images by 5 mm steps from different lens positions in focal axis distances (4, 15, and 30 mm were synthesized. The comparison shows that 15 mm distance has the highest gain and 30 mm distance has the higher image quality. Therefore, there is the possibility to switch from the high gain low-resolution mode to the low gain high-resolution mode by changing the lens position in terms of the feed. The imaging feasibility can be applied at 6G radio systems if adjustable lens systems are used revealing the new potential features in future radios.

KEYWORDS
6G, radio imaging, radio science and propagation, sub-THz, wave propagation

JEL CLASSIFICATION
Electrical and electronic engineering

1 | INTRODUCTION

Recently there has been wide research activity in the field of sub-THz telecommunication and imaging fields presenting different sort of applications also for security screening and spectroscopy areas. Lower THz frequencies (300 GHz) has
been proposed for the candidate of the 6G communication systems that allowing as a high speed as terabit per second. Current 5G telecommunication technology cannot meet previous technical requirements.

At sub-THz frequency, the antenna dimension will be decreased drastically which makes more much difficult to maintain large antenna aperture. If the aperture decreases, the power of the wave propagation is decreased. To overcome the challenge in the technology, lens antennas or phased array antennas have been applied as an alternative approach. Both options can provide higher gain and directivity, but however, the lens antenna is naturally enabling the focal length adjustment for either telecommunication or imaging purposes. The antenna beam is reflected in the lens and widen/reduced beam characteristics can be changed.

Several research works have been focused on dielectric lens antenna modification and circuit components. Elliptical lens geometry could contribute to the gain of 36.5 dB for 110 GHz, and hyperbolic horn lens model aimed by metal guide feeder could perform gain 39 dB at frequency 240 GHz, respectively. The high gain antenna is a key requirement to support the high data rate radio link for the upcoming high frequency communication systems even for short range has been predicted about 100 dB gain so gain enhancing methods with narrow beam properties still is a matter of research. Recently, experimental research has been carried out on the long-range radio link with frequency 300 GHz, the parabolic lens antenna around 55 dB was implemented to provide high bit rate communication for two long distances (500 m and 1 km). Lens antenna with a narrow beam and high directivity has been earlier presented to synthesize image and accurate localization already. Sub-THz frequency (or μwave), among wave to target interaction, the smaller target can be detected by smaller wavelength precisely. Consequently, higher resolution images can be synthesized. The reflected wave at sub-THz frequency is an alternative way to collect information from the target. Combined communications and sensing ideas are presented earlier in References 13–15.

THz imaging has a wide range of applications. Most commonly, it has been used for safety and medical applications. Imaging at 300 GHz was presented in the short (50 cm) and long (2 m) range using fixed lens positions. In telecommunication, lenses are typically fixed to have maximum gain between transmitter and receiver. This means that the object between transmitter and receiver is not in focus. Our research question is related on this phenomenon: If the lens is not fixed, then lens can be focused to the object for imaging or the high gain for communication. This would provide alternative applications that take advantage of existing radio links, which could offer completely new technical features and improve the cost-effectiveness of the 6G radio communication infrastructure in the future.

In this article, a concept of a dual mode operated sub-THz frequency radio system by adjusting the lens-antenna distance for either telecommunication or imaging modes is presented. Bergenia leaf was used as an object for performance evaluation in the short-range continuous wave (CW) radio system. The image of the object was synthesized by aiming the narrow beam width bullet lens towards the leaf and receiver and moving the leaf with the pattern of a 2-dimensional matrix of (20 × 20 by 5 mm step) by utilizing the inverse synthetic-aperture radar technique.

The principle of the concept of the dual mode operated communication and imaging mode radio system is illustrated by schematic diagram in Figure 1. The bullet-shaped lens antenna is implemented at 15 mm antenna to the lens-distance to the transmitter (receiver) waveguide in the telecommunication mode and the radiated beam is collimated or focused to the receiver for the high gain characteristics. In the imaging mode, the bullet-shaped lens antenna is adjusted at 30 mm antenna to lens-distance to the transmitter (receiver) waveguide and the radiated beam is refracted for reduced beam width and the focal point is moved to the object for the high image quality characteristics.

![Figure 1](image-url)
The concept of the dual mode operated communication and imaging mode radio system is demonstrated, and the developed bullet-shaped lens antenna is characterized by simulation and measurements in the following sections. Section 2 will describe a setup for a 300 GHz radio link, a bullet lens antenna is designed, then the radio link is realized by integrating a setup of instruments. Section 3, the object will be placed into the middle radio link, the image of the object is synthesized by the aim of the bullet lens and its displacement in the focal axis direction. Finally, the applicability of the concept is discussed.

2 | EXPERIMENTAL BULLET LENS DESIGN

To reach the narrow beamwidth and high gain the elliptical geometry was applied for lens\(^1,31\) and the bullet-shaped lens antenna was designed by CST microwave Studio\(^32\) at a center frequency of 300 GHz. The lens was fabricated using a room temperature fabrication (RTF) method.\(^33\) A low dielectric permittivity (\(\varepsilon_r = 1.18, \tan \delta = 0.003\)) ceramic composite (LMO-HGMS, the material recipe is presented in Reference 34, for sustainable 6G\(^30\)) was casted in a shape using a molding process. The fabricated lens size was 30 \(\times\) 49.5 mm. The reflection coefficient of the antenna lens was simulated to be below than \(-10.5\) dB for the frequency band from 220 to 330 GHz in Figure 2 owing to the maximum gain of 28 dB with 1° beamwidth (HPBW) at 300 GHz.

3 | EXPERIMENTAL MEASUREMENTS FOR DUAL MODE LENS ANTENNA

To realize the realistic short range over-the-air measurement system the Keysight PNA-X (operating frequency 67 GHz) was connected via cables to a pair of VDI extenders (operating frequency 220 to 330GHz), Tx (transmitter), and Rx (receiver) and it is illustrated into Figure 3. Tx and Rx are placed in reciprocal position and aligned on the same level and positions for the maximum transmitted power. The input power 0 dBm is adjusted to feed on PNA-X to VDI extender which Tx attached to a rectangular standard waveguide WR3.4 and the bullet-shaped lens. To collect the waves (as a receiver), Rx connected via cable to a standard horn antenna of 30dB gain. After the PNA-X calibration in order to find the optimum antenna to lens-distance the lens was located at 21 mm leading to the transmitted signal in the system. Rx cable output as an S21 parameter was recorded in PNA-X. The measurement setup presented in Figure 3 was adjusted for lens characterization, whereas the leaf characterization is applied later in the same system.

The previous measurement setup was used for demonstrating telecommunication and imaging modes by the measurements of three different sample distances (4, 15, and 30 mm) of Bergenia leaf. The imaging technique is called Inverse Synthetic Aperture Radar (ISAR) imaging, where instead of radar sweeping (or across the board) the target is moving. Regarding environment and facilities limitation, the measurement setup Tx and Rx are placed at 50 cm distance.

![Figure 2](image-url) Simulated reflection co-efficient and gain of bullet shape lens antenna

---

****

**FIGURE 2** Simulated reflection co-efficient and gain of bullet shape lens antenna

---

**FIGURE 3** The measurement setup of dual mode lens antenna
For further investigation, the bullet lens beam waist size parameter ($\sigma = 1.2$ mm) was calculated using Equation (1), which is function of wavelength $\lambda_0$ and focal length $f_1$ and lens $D$ diameter:\[\sigma = \frac{2\lambda_0}{\pi \sin \left( \frac{D}{2f_1} \right)}\] (1)

Bergenia leaf was used as object in the measurements (Figure 4A) appearing substantial thickness of 100 $\mu$m in general and 2 mm in water veins. The leaf was placed in the middle of 50 cm distance. Then it is mounted over a plate that has moving capability into three directions (X, Y, and Z) with a controllable stepped motor. All setups were placed at the height of 1.5 m above the earth.

To acquire image of the object, a movement area pattern of 100 mm $\times$ 100 mm was defined for the plate (with leaf) into two Cartesian directions (Y and Z) with the step of 5 mm. It means that the leaf is moved and displaced into the
width of radio link (Y and Z) path but not in focal axis direction (X). The image acquiring procedure is repeated for every lens displacement and images are synthesized by aim of MATLAB algorithm. Here, by displacing lens in three distances to Tx feeder, 4, 15, and 30 mm, three images are synthesized for frequency 300 GHz and displayed in Figure 4B–D, respectively.

The images are synthesized from the measured S21 parameter, the differences in the path loss (right side colorbar) are caused by the different thickness of the leaf and free space loss in the system. Recorded S21 was −45 dB when the lens was at 4 mm distance from the Tx, −40 dB at 15 mm distance and −48 dB at 30 mm distance. So, the system was optimized for maximum transmitted power at 15 mm distance. The synthesized image with the distance of 4 mm is presented in Figure 4B and the image with the distance of 15 mm in Figure 4C. The image resolution in terms of water veins is close to each other. However, the image with the distance of 30 mm (Figure 4D) had the best quality and the image resolution in terms of water veins was clearly improved. In fact, by changing distances, the focal point, and beam waist are changed which impacted the image quality, consequently. When the distance between lens to Tx (4 mm) is decreased, image (Figure 4B) is not clear, but when the distance is increased (30 mm), it means the leaf is in the focus and then the synthesized image quality is improved clearly.

Thus, the principle of the concept of the dual mode operated communication and imaging mode radio system was demonstrated by displacing the lens positions in focal axis direction (X), distance between Tx to lens meaning changing states between high gain and the image resolution, consequently. Briefly, changing the lens position it is possible to switch between the high gain low resolution mode and the low gain high resolution mode, which is demonstrated, experimentally.

The lens antenna implementation is helped to identify the image of assumed objects into the radio system, clearly, even the difference is distinguishable by the eye. Also, the leaf thick and thin part has appeared in the image with dark blue and light yellow based on colorbar indication, respectively. By inspiration of optical imaging, it demonstrated lens antenna performs properly with focal point distance. This high-quality image Figure 4D is thanks to bullet lens parameters include high gain 28 dBi and narrow beamwidth 1°. In addition, the capacity of transmitter lens's focal point adjustment can be used for increasing the radiated field strength in the location of receiver antenna or alternatively decreasing the field strength in the location of the adjacent user.

4 | CONCLUSION

This work demonstrated the upcoming 6G radio system having the substantial potential to be implemented the short-range imaging applications in particular for an object that might appear in the radio channel. The bullet lens with performance parameters including gain 28 dBi and beamwidth 1° was fabricated and implemented into the radio link. It aims to construct the image of the object. The impact of the distance, between lens to transmitter waveguide was varied: 4, 15, and 0 mm. Maximum transmitted power was at optimum 15 mm distance and image quality was at optimum distance of 30 mm, that are representing optimum lens displacement positions for telecommunication and imaging in this system. This is the main outcome of this research. Synthesized images are visible clearly even visually, and it shows by increasing lens distance higher resolution images are synthesized. This setup was successfully demonstrated the imaging mode radio system and confirmed that it has potential to be implement in the upcoming 6G telecommunication systems.

ACKNOWLEDGMENTS
This work was supported partly by Microelectronics Research Unit, Faculty of Information Technology and Electrical Engineering, University of Oulu, Finland and partly by Academy of Finland 6Genesis Flagship (Grant no. 318927).

PEER REVIEW
The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12474.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST
The authors declare no potential conflict of interest.
REFERENCES

1. Kokkonen M, Myllymäki S, Jantunen H. 3×3 dipole lens antenna at 300 GHz with different permittivity lenses. Proceedings of the 2020 2nd 6G Wireless Summit (6G SUMMIT); March 2020:1-4; Levi, Finland. doi: 10.1109/6GSUMMIT49458.2020.9083825

2. Myllymäki S, Teirikangas M, Kokkonen M. BaSrTiO3 ceramic-polymer composite material lens antennas at 220-330 GHz telecommunication applications. *Electron Lett.* 2020;56(22):1165-1167. doi:10.1049/el.2020.1875

3. Lee JN, Cho YK, Jung JH, Hyun SB. High-gain sub-terahertz lens horn antenna with a metal guide. *Electron Lett.* 2020;56(14):689-691. doi:10.1049/el.2020.0860

4. Piksa P, Zvanovec S, Cerny P. Elliptic and hyperbolic dielectric lens antennas in mm-waves. *Radioengineering.* 2011;20(1):270-275.

5. Ghavidel A, Khierdoost A. Broadband millimeter wave planar power combiner/divider. Proceedings of the 2019 International Symposium on Networks, Computers and Communications; 2019:1-4; IEEE. doi: 10.1109/ISNCC.2019.8909088

6. Rikkinen K, Kyösti P, Leinonen ME, Berg M, Pärssinen A. THz radio communication: link budget analysis toward 6G. *IEEE Commun Mag.* 2020;58(11):22-27.

7. Castro C, Elschner R, Merkle T, Schubert C, Freund R. Long-range high-speed THz-wireless transmission in the 300 GHz band. Proceedings of the 2020 3rd International Workshop Mob Terahertz Syst IWMTS 2020:12-15. doi: 10.1109/IWMTS49292.2020.9166532

8. Phippen D, Daniel L, Hoare E, Cherniakov M, Gashinova M. Compressive sensing for automotive 300GHz 3D imaging radar. 2020 *IEEE Radar Conf (RadarConf20).* Florence, Italy, 2020;1–6. doi:10.1109/RadarConf2043947.2020.9266532

9. Barneto CB, Liyanaarachchi SD, Heino M, Riihonen T, Valkama M. Full duplex radio/radar technology: the enabler for advanced joint communication and sensing. *IEEE Wirel Commun.* 2021;28(1):82-88. doi:10.1109/MWC.001.2000220

10. Merrill S. *Introduction to Radar Systems.* 2thed.; McGraw-Hill; 1980.

11. Grzyb J, Statnikov K, Sarmah N, Pfeiffer UR. 3-D high-resolution imaging at 240 GHz with a single-chip FMCW monostatic radar in SiGe HBT technology. Proceedings of the International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz); 2016:1-2. doi:10.1109/IRMMW‐THz.2016.7758437

12. Mostajeran A, Naghavi SM, Emadi M, et al. A high-resolution 220-GHz ultra-wideband fully integrated ISAR imaging system. *IEEE Trans Microw Theory Techn.* 2019;67(1):429-442.

13. Wild T, Braun V, Viswanathan H. Joint design of communication and sensing for beyond 5G and 6G systems. *IEEE Access.* 2021:9;30845-30857. doi:10.1109/ACCESS.2021.3059488

14. Paul B, Chiriyath AR, Bliss DW. Survey of RF communications and sensing convergence research. *IEEE Access.* 2017:5;252-270. doi:10.1109/ACCESS.2016.2639038

15. Rappaport TS, Murdock JN, Gutierrez F. State of the art in 60-GHz integrated circuits and systems for wireless communications. *Proc IEEE.* 2011;99(8):1390-1436. doi:10.1109/JPROC.2011.2143650

16. Lu X, Venkatesh S, Saedii H. A review on applications of integrated terahertz systems. *China Commun.* 2021;18(5):175-201. doi:10.23919/JCC.2021.05.011

17. J. Wang, H. Lindley-Hatcher, X. Chen, and E. Pickwell-MacPherson, “THz sensing of human skin: a review of skin modeling approaches,” *Sensors,* vol. 21, no. 11, Art no 3624, 2021, doi: 10.3390/s21113624

18. Song Z, Yan S, Zang Z, et al. Temporal and spatial variability of water status in plant leaves by terahertz imaging. *IEEE Trans Terahertz Sci Technol.* 2018;8(5):520-527. doi:10.1109/TTHZ.2018.2851922

19. Cassar Q, Al-Ibadi A, Mavarani L, et al. Pilot study of freshly excised breast tissue response in the 300–600 GHz range. *Biomed Opt Express.* 2018;9(7):2930-2942. doi:10.1364/OE.9.002930

20. Mittleman DM. Twenty years of terahertz imaging [invited]. *Opt Express.* 2018;26(8):9417-9431. doi:10.1364/OE.26.009417

21. Etayo D, Iriarte JC, Palacios I, et al. THz imaging system for industrial quality control. Proceedings of the 2011 IEEE MTT-S International Microwave Workshop Series on Millimeter Wave Integration Technologies; September 2011:172-175; Sitges, Spain. doi: 10.1109/IMWS3.2011.6061867

22. Mittleman DM, Jacobsen RH, Nuss MC. T-ray imaging. *IEEE J Sel Top Quant Electron.* 1996;2(3):679-692. doi:10.1109/2944.571768

23. Pawar AY, Sonawane DD, Erande KB, Derle DV. Terahertz technology and its applications. *Drug Invent Today.* 2013;5(2):157-163. doi:10.1016/j.dit.2013.03.009

24. Ghavidel A, Myllymäki S, Kokkonen M, Tervo N, Nelo M, Jantunen H. A sensing demonstration of a sub THz radio link incorporating a lens antenna. *Prog Electromagn Res Lett.* 2021;99:119-126. doi:10.2528/PIERL21070903

25. Volakis J. *Antenna Engineering Handbook.* 4thed. McGraw-Hill; 2007.

26. 6G Flagship. 6G radio – THz sensing demo; September 03, 2021. Accessed September 07, 2021. https://youtu.be/TL1BcleFORs

27. Uusitalo MA, Ericson M, Richerzhagen B, et al. Hexa-X the European 6G flagship project. Proceedings of the 2021 Joint European Conference on Networks and Communications 6G Summit (EuCNC/6G Summit); June 2021:580-585; Porto, Portugal. doi: 10.1109/EuCNC/6GSummit51104.2021.9482430
28. Liyanaarachchi SD, Barneto CB, Riihonen T, Valkama M. Experimenting joint vehicular communications and sensing with optimized 5G NR waveform. Proceedings of the 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring); April 2021:1-5; Helsinki, Finland. doi: 10.1109/VTC2021-hyphen;Spring51267.2021.9448834

29. Rappaport TS, Xing Y, Kanhere O, et al. Wireless communications and applications above 100 GHz: opportunities and challenges for 6G and beyond. IEEE Access. 2019;7:78729-78757. doi:10.1109/ACCESS.2019.2921522

30. Saarela H, Wittenberg V. 6G waves magazine: spring 2021. University of Oulu, 2021. Accessed September 14, 2021. [Online]. http://urn.fi/urn:isbn:9789526228983

31. Sauleau R, Fernandes CA, Costa JR. Review of lens antenna design and technologies for mm-wave shaped-beam applications. Proceedings of the 11th International Symposium on Antenna Technology and Applied Electromagnetics [ANTEM 2005]; June 2005:1-5; St. Malo. doi: 10.1109/ANTEM.2005.7852157

32. CST studio suite 3D EM simulation and analysis software; 2012. Accessed August 25, 2021. https://www.3ds.com/products-services/simulia/products/cst-studio-suite/.

33. Kähäri H, Teirikangas M, Juuti J, Jantunen H. Improvements and modifications to room-temperature fabrication method for dielectric Li2MoO4 ceramics. J Am Ceram Soc. 2015;98(3):687-689. doi:10.1111/jace.13471

34. Kokkonen M, Nelo M, Chen J, Myllymäki S, Jantunen H. Low permittivity environmentally friendly lenses for Ku band. Prog Electromagn Res Lett. 2020;93:1-7. doi:10.2528/PIERL20060108

35. Saleh BEA, Teich MC. Fundamentals of Photonics. 2nd ed. Wiley-Interscience; 2007.

How to cite this article: Ghavidel A, Myllymäki S, Kokkonen M, Tervo N, Jantunen H. Lens antenna adjustment for telecommunication and imaging modes in a sub-THz radio system. Engineering Reports. 2022;4(3):e12474. doi: 10.1002/eng2.12474