Wireless At Sub-millimeter waves: Signals, Antennas and Photonics (WASSAP)

1. Summary of the project

The goal of this project was to develop both hardware components and signal processing tools to facilitate the adoption of **sub-terahertz (sub-THz) frequency bands** for efficient, high data rate wireless communications. Specifically, considering the typically low available power levels in this frequency range and the high free-space propagation losses (which are proportional to the square of the frequency), one of our objectives was to ensure that all generated power is transmitted directly toward the receiver. To achieve this, we considered two different scenarios: near-field and far-field communications.

For efficient transmission in the near-field scenario, we employed **non-diffractive Bessel beam launchers**. These launchers take advantage of their non-diffractive properties over a limited range and possess the ability to reconstruct themselves after encountering an obstacle. In contrast, for far-field applications, we investigated **high-gain beam-steering antennas**. These antennas help mitigate propagation losses, which increase with the square of the distance between the transmitter and receiver, by utilizing spatially narrow beams that can be precisely directed toward the receiver.

Furthermore, for both types of radiators, we employed **photonic generation of sub-THz signals** through photomixing [J1]. This approach allowed the generated sub-THz signals to be tunable over a wide bandwidth, enabling the use of optical modulation schemes and reliable and cost-effective optical amplifiers (EDFA, SOA) and ensuring seamless integration with fiber networks. In addition, both near-field and far-field antennas needed to be **appropriately characterized** before being used in a communication link; this was another aspect addressed in this project.

Finally, the last challenge involved providing **suitable waveforms** for single-carrier (SC) modulations in the sub-THz regime, focusing on their robustness to sub-THz impairments (such as phase noise, non-linear effects, and I/Q mismatch). Other aspects analyzed include equalization and synchronization at the receiver (frequency, timing, and phase), as well as Forward Error Correction (FEC).

2. Results of the project

2.1. Near-field links

We leveraged the **self-healing feature of Bessel beams** to establish a wireless link that remains resilient to opaque metallic obstructions, ensuring error-free, high data rate transmission at W-band. This capability was experimentally confirmed by placing a circular metallic obstacle within the non-diffractive region of the Bessel beam. The near field radiated by a broadband launcher, comprising a photonic transmitter and a spline-profile horn, was measured both with and without obstacles, and the corresponding field distributions are compared. The Bessel-beam profile was preserved after the obstacle over the 75–105 GHz band. The power transmission measurements reported, to the best of our knowledge, the most efficient broadband beam transfer efficiency ever demonstrated within the W-band, over distances ranging from 10 to 30 free-space wavelength, reaching a maximum of 70% at 99 GHz.

To further assess the robustness of the near-field link with and without obstructions, transmission characteristics and bit error rates (BER) were measured in both scenarios. Additionally, real-time error-free communication was achieved for a 3 Gb/s data stream using on-off keying modulation [C8] within the non-diffractive range of the generated Bessel beams [see Fig. 1(a)]. Higher data rates were obtained for an offline QPSK link at 15.5 Gb/s (BER < 10^{-5}) [C13],[C14].

2.2. Far-field links

For far-field links we have designed a high-gain, photonic-enabled phased array as a scalable solution for high-speed communications, showcasing a 26 dBi directivity array with a wide relative bandwidth of

30% (85 GHz to 115 GHz). This design is fully compatible with standard high-density interconnect (HDI) printed circuit board (PCB) processes, and it also includes the DC-biasing network of the uni-traveling-carrier photodiodes (UTC-PDs) from III-V labs used as photomixers [C4],[C7]. This design, shown in Fig. 1(b), not only incorporates beam steering but also leverages the power combining capabilities of high-power THz sources to enhance transmission efficacy. Moreover, we propose and demonstrate a novel method for generating the sub-THz carrier using a dual frequency laser and subsequently continuously tune in the optical domain the phase of each radiating element of the array in a cost-effective and efficient manner.

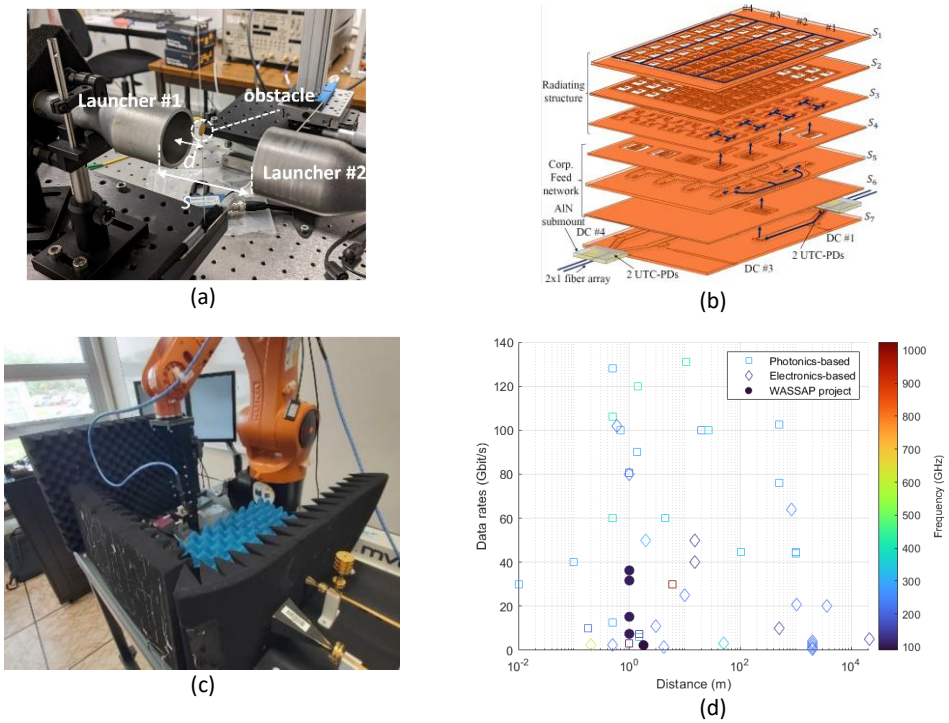

Fig. 1. Graphical abstract. (a) Experimental set-up for measuring the BER using the two fabricated Bessel beam launchers separated by a distance *s* and with a circular metallic obstacle placed at a distance of *d*=9.4 mm from the aperture of the first launcher. (b) Exploded view of the high-gain, photonic-enabled phased array design. (c) 6-axis robotic arm used in the bench for phase less sub-THz antenna measurements. (d) Data rates versus distance and carrier frequency of sub-THz and THz communications.

2.3. Sub-THz Antenna Metrology

IMT Atlantique has developed a measurement bench for characterizing the 3D radiation patterns of millimeter-wave and sub-THz antenna systems. Measurements are conducted in the near-field, eliminating the need to meet far-field distance requirements, which helps maintain compactness. The system uses a 6-axis robot [shown in Fig. 1(c)] to move a probe around the device under test. The main advantage of this setup is that the device remains stationary, making it particularly convenient for measuring on-chip antennas or the photomixing arrays developed in this project.

Near-field measurements of high-gain antennas can be performed using both amplitude and phase data to compute the far-field radiation pattern. However, phase measurement is a critical challenge, as it is highly sensitive to factors such as cable position and curvature. Since millimeter-wave antennas are typically integrated into the RF front-end, accessing a phase reference can be difficult. The originality of this robotic measurement bench lies in its ability to characterize devices without relying on phase measurements, using a technique known as phase less measurement.

2.4. Signal Processing and Waveforms

Multiple waveforms have been studied, ranging from linear Phase-and-Amplitude Modulations (PAM), such as QPSK and 16-QAM, to non-linear Continuous Phase Modulations (CPM), such as RC and GMSK. These waveforms have been compared with each other, with phase noise considered as the main impairment [C1],[C2].

Measurement campaigns were conducted to compare the performance of several different waveforms: GMSK, RC, QPSK-2-FSIM (from [1]), QPSK, and 16-QAM. The key result from these campaigns is a working demonstrator operating at a carrier frequency of 107.5 GHz, achieving data rates of 7.4 Gbps (error-free) for CPM waveforms, 15.2 Gbps (error-free) for QPSK, 31.7 Gbps (with a BER on the order of 10^{-4}) for QPSK-2-FSIM, and 36.3 Gbps (with a BER on the order of 10^{-2}) for 16-QAM, with a transmission distance of 1 meter between the transmitting and receiving antennas.

3. Indicators

3.1. Defended theses

Two PhD thesis will be defended by the end of the year:

- Paul Desombre.
- Jérôme Taillieu.

3.2. Elements of international visibility

- Mr. Mauro ETTORRE and Mr. David GONZALEZ OVEJERO, CNRS researchers in the SUMIT team at IETR, won the Best Paper Award at the International Workshop on Antenna Technology (iWAT) conference, held in Aalborg, Denmark, from May 15 to May 17, for their paper titled: “High Speed and Resilient Wireless Interconnects in the Near Field.” https://www.ietr.fr/mauro-ettorre-et-david-gonzalez-ovejero-remportent-le-prix-du-meilleur-article-linternational
- Mr. Jérôme Taillieu, a PhD student from the SUMIT team at IETR, won the Young Scientist Award at the Atlantic Radio Science Meeting organized by the International Union of Radio Science (URSI) in Gran Canaria, Spain, from May 19 to 24, for his paper: “High Data-Rate Sub-THz Coherent Near-Field Wireless Links Enabled by Spline-Profile Bessel Launchers.” https://www.ietr.fr/jerome-taillieu-obtenu-le-young-scientist-award-la-conference-4th-atlantic-radio-science-meeting
- Mr. Jérôme Taillieu, a PhD student from the SUMIT team at IETR, was finalist for the Best Applied Technology Antenna Paper Award at the 18th Eur. Conf. Antennas Propag. (EuCAP) for his paper “High Data-Rate Sub-THz Coherent Near-Field Wireless Links Enabled by Spline-Profile Bessel Launchers”. (https://www.eucap2024.org/nomineesoftheeucapbestpaperawards)

3.3. Publications

During the project, we have published:

- 4 national peer-reviewed conference papers
- 14 international peer-reviewed conference papers
- 3 international peer-reviewed journal papers

Other publications are under review and in preparation.

3.3.1. National Conference papers

[N1] R. Cane, J. Taillieu, D. Gonzalez-Ovejero, R. Sauleau, and M. Alouini, “Cellule elementaire controlable optiquement pour reseau-transmetteurs en bande X,” *Optique Dijon 2021*, Société Française d’Optique, Jul 2021, Dijon, France.

[N2] F. Gallée, C. Kärnfelt, D. Zelenchuk, I. Munina, M. Sinou, et al, “Antenne lentille de type Lüneburg réalisée en LTCC pour 60 GHz,” *22èmes Journées Nationales Microondes*, Jun 2022, Limoges, France. https://imt-atlantique.hal.science/hal-03752358

[N3] J. Taillieu et al., "Réseau d'antennes à photo-mélange pour commutation photonique de faisceau en ondes millimétriques," *22èmes Journées Nationales Microondes*, Jun 2022, Limoges, France. pp.815-818. https://hal.science/hal-03700274

[N4] J. Taillieu, D. González-Ovejero, W. Fuscaldo, L. Bramerie, P. Desombre, M. Gay, M. Alouini, H. Farès, Y. Louët, M. Ettorre, "Faisceaux de Bessel à courbes de spline pour les liens sub-millimétriques cohérents en champ proche à très haut debit" *23èmes Journées Nationales Microondes*, Jun 2024, Antibes, France.

3.3.2. International Conference papers

[C1] P. Desombre, H. Farès and Y. Louët, "Performance Comparison of Digital Modulations in the Presence of Gaussian Phase Noise in the Sub-THz Context," *4th Int. Workshop Mobile THz Syst. (IWMTS)*, Essen, Germany, 2021, pp. 1-5. https://hal.science/hal-03323900

[C2] P. Desombre, H. Farès, Y. Louët, "Waveform comparison in the presence of Gaussian Phase Noise in the sub-THz context" URSI-GASS, Aug 2021, Roma, Italy. https://hal.science/hal-03337752

[C3] D. Zelenchuk, C. Kärnfelt, F. Gallée and I. Munina, "Metamaterial-based LTCC Compressed Luneburg Lens Antenna at 60 GHz for Wireless Communications," *IEEE Int. Conf. Microw. Antennas Commun. Electron. Syst. (COMCAS)*, Tel Aviv, Israel, 2021, pp. 513-515.

[C4] J. Taillieu, R. Sauleau, M. Alouini and D. González-Ovejero, "Cavity-Backed Broadband Microstrip Antenna Array for Photonic Beam Steering at W Band," *16th Eur. Conf. Antennas Propag. (EuCAP)*, Madrid, Spain, 2022, pp. 1-5, https://hal.science/hal-03771389

[C5] M. Younes, P. Desombre and Y. Louet, "Trade-off between spectral and energy efficiency in THz frequency bands for 6G," *1st Int. Conf. 6G Netw. (6GNet)*, Paris, France, 2022, pp. 1-5, doi: 10.1109/6GNet54646.2022.9830241.

[C6] D. Khezzar, D. Khedrouche, C. Kärnfelt, A. T. Denidni and F. Gallée, "CPW-Fed LTCC Based Broadband Microstrip Antenna for Millimeter-Wave Applications at 60 GHz," *19th Int. Multi-Conf. Syst. Signals Devices (SSD)*, Sétif, Algeria, 2022, pp. 438-443 https://hal.science/hal-03670233

[C7] J. Taillieu, R. Sauleau, M. Alouini and D. González Ovejero, "Modulated metasurface array for photonic beam steering at W band," *17th Eur. Conf. Antennas Propag. (EuCAP)*, Florence, Italy, 2023, pp. 1-4, https://hal.science/hal-04223033

[C8] M. Ettorre and D. González Ovejero, "High Speed and Resilient Wireless Interconnects in the Near Field," *Int. Workshop Antenna Technol. (iWAT)*, Aalborg, Denmark, 2023, pp. 1-4, https://hal.science/hal-04192485

[C9] D. González-Ovejero, J. Taillieu, C. Bilitos, R. Sauleau, O. de Sagazan, "Modulated metasurface antennas and arrays for millimeter wave and sub-terahertz applications," *13th Int. Conf. Metamaterials, Photonic Crystals and Plasmonics (META)*, Jul 2023, Paris, France. pp.858-859. https://hal.science/hal-04282532

[C10] P. Desombre et al., "Continuous Phase Modulations for Sub-THz Wireless Communications," *XXXVth General Assembly Sci. Symp. Int. Union Radio Sci. (URSI GASS)*, Sapporo, Japan, 2023, pp. 1-3. https://hal.science/hal-04265021

[C11] R. Allanic et al., "Monolithic Co-Design of a 15 GHz SPDT-Antenna Allowing Polarization Reconfigurability," *IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Portland, OR, USA, 2023, pp. 117-118

[C12] M. Mehraz, F. Gallée, "Impact of measurement parameters on antenna radiation pattern reconstruction using phaseless iterative technique," *IEEE Conf. Antenna Meas. Applications (CAMA)*, Nov 2023, Genoa, Italy, pp.101-104. https://imt-atlantique.hal.science/hal-04449493

[C13] J. Taillieu, D. González-Ovejero, W. Fuscaldo, L. Bramerie, P. Desombre, M. Gay, M. Alouini, H. Farès, Y. Louet, M. Ettorre, "High Data-Rate Sub-THz Coherent Near-Field Wireless Links Enabled by Spline-Profile Bessel Launchers," *18th Eur. Conf. Antennas Propag. (EuCAP)*, Glasgow, UK, 2024, pp. 1-4.

[C14] J. Taillieu, D. González-Ovejero, W. Fuscaldo, L. Bramerie, P. Desombre, M. Gay, M. Alouini, H. Farès, Y. Louet, M. Ettorre, "High Data-Rate Sub-THz Coherent Near-Field Wireless Links Enabled by Spline-Profile Bessel Launchers" *4th URSI Atlantic Radio Sci. Meeting*, Gran Canaria, Spain, 2024.

3.3.3. Journal papers

[J1] Á. J. Pascual et al., "Photonic-Enabled Beam Switching Mm-Wave Antenna Array," *J. Lightwave Technol.*, vol. 40, no. 3, pp. 632-639, 1 Feb.1, 2022, doi: 10.1109/JLT.2021.3124092 https://hal.science/hal-03480488

[J2] D. Zelenchuk, V. Kirillov, C. Kärnfelt, F. Gallée, I. Munina, "Metamaterial-based LTCC compressed Luneburg lens antenna at 60 GHz for wireless communications" *Electronics*, 2023, 12 (11), pp.2354

[J3] P. Desombre, H. Farès and Y. Louët, "Continuous Phase Modulation Proposal for Photonics-Wireless Sub-THz Transmissions," *IEEE Access*, vol. 12, pp. 100217-100229, 2024