Personal Radars for Radio Imaging and Infrastructure-less Localization (PRIMELOC)

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ABSTRACT
This document illustrates the main outcomes of the PRIMELOC project, targeted to provide the first proof-of-concept of the personal radar idea. The personal radar is conceived as a milestone technology towards indoor radio imaging and infrastructure-less localization systems through the design of massive millimetre wave antenna arrays and advanced signal processing algorithms implementing radio-based simultaneous localization and mapping. The follow up of the project to scale the technology to higher TRL is envisioned together with its potential impact on the areas of scientific research, industry and societal challenges.

Keywords: Personal radar; antenna array; millimetre wave; radio-SLAM.

1. INTRODUCTION

The main objective of PRIMELOC was to provide the first proof-of-concept of the **personal radar** as a milestone technology towards indoor radio imaging and infrastructure-less high-accuracy localization systems. This concept stems out from the millimetre-wave (mmWave) technology, which opens the possibility to pack hundreds of antenna elements in a credit card-sized area, thus providing personal devices (e.g., smartphones) with near pencil-beam radio scanning capabilities. Therefore, personal devices can be turned into personal radars to accurately scan the surroundings via beamforming, thus inferring a local map through the collection of radio echoes reflected by walls and objects. Jointly with the generation of the map, the localization of the user in the actual environment is carried out by the personal radar which, in turn, provides the basis for infrastructure-less, zero-cost, non-intrusive and accurate indoor localization systems.

PRIMELOC envisions a future where location-based services, enabled in outdoors by Galileo or GPS, will be widely available also indoors, thanks to the possibility of inferring maps and user locations without the need of a dedicated infrastructure. In fact, maps will be automatically generated and updated by users that will collaborate with each other by exchanging their local information (e.g., through crowdsensing). Indeed, the pervasive diffusion of billions of mobile personal devices will impressively extend the availability of indoor maps with respect to the level that would be achieved using dedicated devices (e.g., robots with laser scanner).

The proof-of-concept of the personal radar has been achieved in PRIMELOC by (i) designing massive mmWave antenna arrays, as enabling technology for the personal radar concept, (ii) by conducting extensive measurement campaigns in real environments (iii) by developing advanced signal processing algorithms for radio-based simultaneous localization and mapping (Radio-SLAM).

The main results obtained in PRIMELOC are summarized in the following:

- A 400-element reconfigurable (smart) surface transmitarray antenna in the mmWave [26-32] GHz frequency band has been designed and employed in a radar measurement setup. The considered smart surface allows an electronically steerable beam with near pencil-beam capabilities of 5 degrees angular scanning resolution;
- Extensive measurement campaigns of the backscatter response of real environments at mmWave have been carried out;
- Dedicated mapping and Radio-SLAM algorithms have been designed and implemented including a specific statistical observation model of radar signals;
- A proof-of-concept about the possibility to realize radio–based "mapless" and "infrastructure-less" indoor localization with decimeter-level localization accuracy has been provided using measured data.

2. STATE OF THE ART

Accurate indoor localization requires the knowledge of the environment's map and the availability of dedicated infrastructures and vice-versa. This “chicken or the egg” dilemma has been addressed by the signal processing community by introducing SLAM methods taking advantage of the capabilities offered by laser-based radars (LIDAR) or cameras (V-SLAM) [1]. Unfortunately, LIDAR devices are usually expensive, energy-hungry, and their usage is somehow constrained for safety reasons. Like LIDAR, V-SLAM requires active user participation to work.

Due to these problems, a conceptual and technological shift was proposed in [2] and developed in PRIMELOC through the introduction of the personal radar concept using Radio-SLAM algorithms.

For the time being, some studies have investigated the problem of reinforcing the localization performance of mobile devices by treating the radio echoes as if they were generated by “virtual” reference nodes, in addition to the actual reference nodes (thus with the need of an infrastructure) [3]. To avoid the infrastructure, other studies addressed the exploitation of existing radio frequency signals as sources of opportunity (Wi-Fi Slam, Deep Map), but with scarce resolution and accuracy.

A key ingredient in PRIMELOC is the design of a massive mmWave antenna array. Phased array solutions are generally based on analog or fully-digital architectures. However, the high insertion-loss and low radiation efficiency at mmWave prevent the use of these architectures for large arrays. The emergent transmitarray technologies, based on smart surfaces, have been proven able to realize high gain antennas with fixed [4], switched, and electronically reconfigurable beams [5-6]. On the one side, for large antenna apertures, the spatial feeding mechanism in transmitarrays drastically reduces the loss and complexity of the power division network compared to classical phased array architectures. On the other side, PCB technologies are compatible with the integration on the array aperture of p-i-n diodes, RF-MEMS switches, varactors, etc., which can be used to easily implement the control of the phase distribution of the antenna aperture without using complex and lossy phase shifters.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Accurate mapping is nowadays realized with dedicated laser- or vision-based technologies with mechanical or user-driven steering, thus making extensive mapping of indoor environments infeasible due to practical and economic reasons. Moreover, highly accurate indoor positioning would require an ad-hoc infrastructure that is not always possible, thus preventing a pervasive diffusion of position-aware indoor services.

Starting from these impediments, in PRIMELOC we addressed, theoretically and experimentally, the challenging problem of inferring simultaneously the topology of the environment and the position of the user by analysing the backscattered signal (radio image) received at the user’s terminal, without the help of a dedicated infrastructure (Radio-SLAM).

Towards this objective, the project focused on the design of electronically steerable massive antenna arrays at mmWave with beam shaping and near pencil-beam capabilities to enable high-definition personal radar capabilities, and on the design of innovative algorithms to infer ambient maps from radio images as well as the user’s location. Specifically, a transmitarray antenna has been employed by realizing a smart surface composed of 400 elements in 10.2 x 10.2 cm². It is based on linearly polarized 1-bit unit-cells with 180° phase-shifting capability, combined with sequential rotation schemes to generate a circularly polarized beam over a broad frequency band. The use of such a large number of antennas represents a major breakthrough in the field of sensor/radar, paving the way towards new functionalities enabled by the high directivity and 3D scanning capabilities.

Radio-SLAM is not a mere application of LIDAR/Vision SLAM algorithms to radio signals, but it has required the design of *ad hoc* statistical observation models and signal processing methods to account for the peculiarity of backscattered radio signals, such as antenna sidelobes, multipath, and dominant specular reflections.

It is our opinion that the breakthroughs of PRIMELOC do not lie only in the design of the singular components of the system (e.g., antenna array, Radio-SLAM algorithms), but also on the whole personal radar concept and on its experimental validation. With respect to the state-of-the-art, the above-outlined breakthroughs are expected to revolutionize the way indoor mapping and localization are obtained. The disruptive result is that, in perspective, neither infrastructure nor economical effort will be required to provide mapping and localization services inside buildings, thus filling the gap between outdoors and indoors. We foresee that within ten years the personal radar will be embedded in smartphones generating an impact similar to that of satellite-based outdoor mapping/positioning.

4. PROJECT RESULTS

The core results of PRIMELOC are highlighted in the following.

A 400-element smart surface transmit-array antenna in the mmWave [26-32] GHz frequency band has been implemented in a radar measurement setup, shown in Fig. 1(a)-(b). The logic circuit of smart surface control, i.e., the phase distribution on 400 elements, was realised on an electronic board which has the same size of the array and is collocated with the focal source. The scanning capabilities were first verified in anechoic chamber, showing a maximum gain of around 20 dBi, corresponding to a half power beam width less than 6°, and a side lobe level less than 20 dBi (Fig. 1-c).

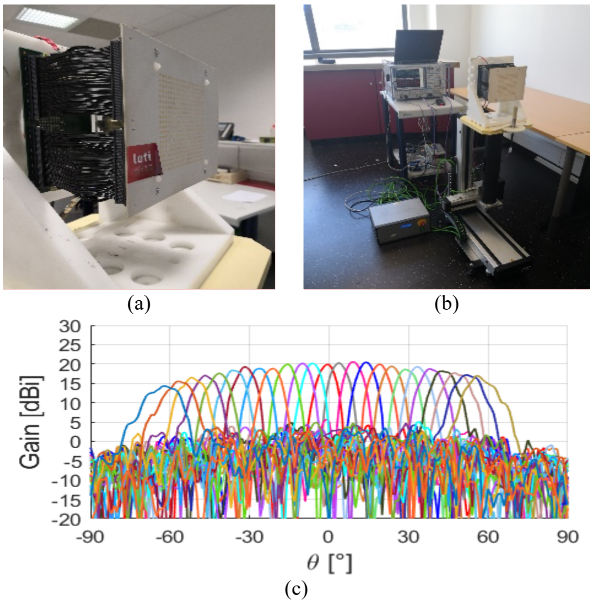

Fig. 1. 400 elements smart surface antenna (a), radar measurement setup (b), and measured gain patterns for +/- 60° steering angels (c).

The step-frequency radar was set to realize a frequency sweep with steps of 5 MHz. The full mmWave band is sounded in a quasi-monostatic radar configuration where on the receiver side a +/- 60° degrees electronic beam scan is operated. Measurements have been performed in several indoor environments, by employing a 3-D axis robot to displace the antenna in different positions.

Radio signals backscattered by the environment have to be properly processed in order to infer the map of the scenario and, in parallel, track the position of the mobile user (personal radar). The general processing flow designed and tested is sketched in Fig. 2 (left). Sequences of angle-range radar images (frames) are acquired by the antenna and first passed through algorithms called CLEAN and CFAR. Their purpose is to mitigate the presence of artifacts deriving from antenna sidelobes which may generate "ghost" reflections and, hence, confuse the mapping and SLAM functions that are operated successively. The "cleaned" frames represent the input to the Radio-SLAM module whose purposes are i) to estimate the user's pose variations and ii) to map the environment by combining the pose estimates and frames. Pose estimate has been inferred through approaches based on phase-only matched filtering of the Fourier-Mellin transform and correlative scan matching applied to consecutive frames, subsequently filtered by a Kalman filter. They allow the estimate of the rotation and position shift of the user with respect to the previous signal acquisition. Mapping has been obtained through a method based on occupancy grid which exploits a statistical observation model of the radar signal to account for the non-ideal beam width of the antenna pattern.

In Fig. 2 (right), an example of Radio-SLAM obtained by processing measured data is reported. It refers to a user moving along a circular trajectory within a room of size 6 x 12.6 m^2 with some plywood partitions. By comparing the true trajectory with that estimated by the Radio-SLAM algorithm it can be seen that decimetre-level localization accuracy can be achieved in a real scenario. Moreover, results provide an important indication about the feasibility of the personal radar concept, where mapping and self-localization can be obtained using the mmWave technology without a dedicated infrastructure. The technical details and further results of PRIMELOC can be found in [8-11].

5. FUTURE PROJECT VISION

5.1. Technology Scaling

PRIMELOC realized the first proof-of-concept of personal radar enabled by smart surface massive antenna arrays at mmWave, employing lab instrumentation and ad hoc radio-SLAM algorithms. The PRIMELOC concept has been developed and the targeted performance has been demonstrated by means of experimental data (TRL 3-4). The main critical functions have been identified, suggesting a scaling at higher frequency (sub-THz). In fact, in the sub-THz band it is possible to exploit the diffuse scattering from the environment more effectively than in the mmWave band. Moreover, more antenna elements can be packed in the same area, allowing for a sharper beam (i.e., better angular resolution) and integration in mobile phones, with a consequent enhancement of the mapping and Radio-SLAM performance. In perspective, sub-THz/THz technology will be an ingredient in 6G wireless networks, where imaging, localization and communication functionalities are expected to be integrated [7].

In order to assess and improve the personal radio performance in a relevant operational environment (TRL 5-6), the scaling will be achieved in PRIMELOC Phase 2 through three main steps:

1) Development of a SLAM-oriented radar module at sub-THz band, with SiP-level integration of a focused massive antenna system. A first prototype of array at sub-THz with a fixed beam has been recently implemented at CEA-LETI and it will be enhanced towards full electronic beam steering;
2) Optimization of radio-SLAM processing in sub-THz bands, considering hardware impairments and real-time processing. Crowd-based Radio-SLAM algorithms will be investigated with the support of machine learning approaches and data fusion with data coming from other sensors (e.g., inertial, vision);
3) Performance assessment and test report in relevant application scenarios. How to embed this technology in next generations mobile devices will be an important aspect to be considered.

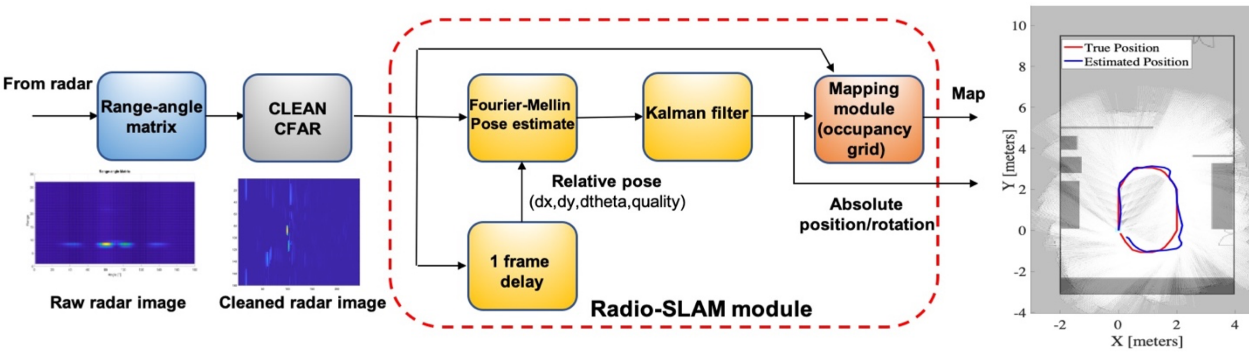

Fig. 2. High-level scheme of the signal processing chain implementing the radio-SLAM (left). Example of reconstructed map and user's trajectory using measured data and radio-SLAM algorithms (right).

5.2. Project Synergies and Outreach

In order to achieve the objectives and increase the TRL, PRIMELOC Phase 2 should last 3 years and the expected cost is estimated to be around 1.8 Million Euros, also considering the high cost for HW implementation in the THz band. The current consortium will be enlarged to include, in addition to the University of Bologna (UNIBO) and CEA-LETI, at least one stakeholder in the field of wireless communications (collaborations are already established with Thales Comm. and ST microelectronics), as well as an end-user related to one of the applications/scenarios illustrated in section 5.3 for technology exploitation. One option to reinforce the consortium is to exploit the network established by the Italian National Consortium for Telecommunications (CNIT) to which UNIBO belongs, which has recently founded the National Laboratory for Wireless Communications (WiLAB) at UNIBO. Moreover, a new division at CEA-LETI working on IC design, THz and radar technology will be involved.
The following exploitation and dissemination strategy will be followed:

- Scientific, R&D, Industrial fora, including single partners initiative (i.e. LETI innovation days);
- Patent filing and licensing;
- Exploitation of the agreement between the University of Bologna and venture capitalist networks;
- Exploitation of CEA-LETI business development unit;
- Start-up creation instruments (UNIBO & CEA-LETI).

Additionally, PRIMELOC Phase 2 will, as part of its dissemination & exploitation plan, engage with European Technology Platforms such as Networld2020 (both CNIT and LETI are in the steering board) and EPoSS. Moreover, LETI and CNIT are elected members of 5G-PPP. This will build upon the large network of industrial contacts brought together by the partners.

5.3. Technology application and demonstration cases

The demonstrator that will be developed in PRIMELOC Phase 2 will be aimed at validating the personal radar technology at sub-THz band in a relevant operational environment. Specifically, it will be demonstrated that it is possible to infer a global map of indoors by combining local radar returns collected in the sub-THz band by different users and localize them simultaneously with high-accuracy without infrastructures. The availability of personal radar capabilities on next-generation portable devices, made possible by the breakthroughs introduced by the PRIMELOC Phase 2, will spur the diffusion of user-generated high-definition indoor maps powering a new generation of immersive location-based applications and services. This will impact a number of different vertical domains, including but not limited to:

- *Industry*: automatic navigation of robots (including unmanned aerial vehicles) in factories and/or hazardous environments;
- *Safety*: guidance in unknown and dangerous environments (e.g., firemen);
- *Wellbeing*: visually impaired people guidance; assisted living for handicapped or elderly persons; non-invasive tracking of pandemic situations similar to Covid-19;
- *Retail/tourism*: personalized guidance, virtual/augmented reality.

The European Commission (EC) estimates that 7% of the European Gross Domestic Product –GDP– is already related to outdoor satellite navigation. Considering that we spend only 7% of our time outdoors, we can only imagine what would be the societal and economic impact if we enabled a counterpart for indoor spaces. The global indoor location market size is expected to grow from USD 6.1 Billion in 2020 to USD 17 Billion by 2025, at a Compound Annual Growth Rate (CAGR) of 22.5% during the forecast period. By overcoming two of the main obstacles threatening the growth of such a market (namely the availability of indoor maps and the cost of positioning technology infrastructures), PRIMELOC Phase 2 will put the basis for the projected growth and lower the entry barrier to the market.

5.4. Technology commercialization

At short term, the outcomes of PRIMELOC in the domains of mmWave radios, antennas and propagation channel, as well as SLAM radar schemes will be protected through patents whenever possible. Internally, CEA and UNIBO will use the project results to update their strategy and roadmaps on 6G and mmWave wireless technologies. UNIBO and CEA have long-lasting relationships with large companies, intermediate and small-medium enterprises of multiple sectors, involved in wireless communications (original equipment suppliers, chip manufacturers) and other areas as end-users. Some of these industries have already shown a great interest in the convergence of radio and radar for 6G devices. PRIMELOC strategy is to transfer its knowledge to these European industries through licensing of intellectual property or to foster the creation of spin-offs if applicable. Some of the demonstration results of the project will be showcased to the industrial partners, through the support of CEA Marketing and Communication Team. The researches carried out in the project will also be promoted in the *Leti Days* events organized by CEA-LETI once a year in France, Japan and USA.

5.5. Envisioned risks

The ground-breaking nature of the project brings some risks that will all be tackled. The main risks (R) that are identifiable at this stage and possible mitigation actions (A) are here summarized:

- (R): Limited sensibility or dynamic range of the RF front-end (Medium). (A): Reduction of the operating range and/or replacement with lab instruments;
- (R): Implementation issues of electronic steering @ THz (Medium). (A): Adoption of fixed beam transmitarray antennas @ THz available at LETI for preliminary tests;
- (R): Delay shift in HW availability (Medium). (A): Processing of instrument-generated data;
- (R): Insufficient performance of SLAM when using data from different users (High). (A): Data fusion with other means (e.g., inertial sensors) and exploitation of signals of opportunity (e.g, Wi-Fi).

5.6. Liaison with Student Teams and Socio-Economic Study

During the project, a MSc student exchange took place between the partners (Ms. Marina Lotti). In the second phase of PRIMELOC, we foresee the involvement of MSc students from different courses (e.g., Industrial design) also through the organization of contests where student teams will be requested to propose ideas on applications of the PRIMELOC technology.
The presence of a stakeholder in the partnership will help in understanding the impact of the personal radar technology embedded in mobile devices through market analysis. The impact on society depends not only on technical aspects but also on the level of user acceptance and cooperation. Within the University of Bologna, the Departments of Electrical Engineering and of Psychology have an already established collaboration that could be exploited to study aspects related to human-machine interaction (technology usability/appealing), privacy and incentive issues through dedicated interviews and involvement of MSc students.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] C. Cadena et al., 2016. Past, present, and future of simultaneous localization and mapping: toward the robust perception age, IEEE Trans. on Robotics, 32(6): pp. 1309–1332.
[2] F. Guidi, A. Guerra and D. Dardari, 2016. Personal Mobile Radars with Millimeter-Wave Massive Arrays for Indoor Mapping, IEEE Transactions on Mobile Computing, 15(6): pp. 1471-1484.
[3] K. Witrisal et al., 2016. High-Accuracy Localization for Assisted Living: 5G systems will turn multipath channels from foe to friend, IEEE Signal Processing Magazine, 32(2): pp. 59-70.
[4] F. Diaby, et al., 2018. Circularly polarized transmitarray antennas at Ka-band. IEEE Antennas and Wireless Propagation Letters, 17(7), 1204-1208.
[5] C. Cheng et al., 2009. A programmable lens-array antenna with monolithically integrated MEMS switches. IEEE Trans. on Microwave Theory and Techniques, 57(8), 1874-1884.
[6] L. Di Palma et al., 2016. Circularly-polarized reconfigurable transmitarray in Ka-band with beam scanning and polarization switching capabilities. IEEE Trans. on Antennas and Propagation, 65(2), 529-540.
[7] H. Sarieddeen, N. Saeed, T. Y. Al-Naffouri and M. Alouini, 2020. Next Generation Terahertz Communications: A Rendezvous of Sensing, Imaging, and Localization, IEEE Communications Magazine, 58(5): pp. 69-75.
[8] D. Dardari et. al., 2020, Experimental validation of the Personal Radar concept, Working paper.
[9] A. Guerra, F. Guidi, D. Dardari and P. M. Djurić, 2020. Reinforcement Learning for UAV Autonomous Navigation, Mapping and Target Detection, IEEE/ION Position, Location and Navigation Symposium (PLANS), Portland, OR, USA, 2020, pp. 1004-1013.
[10] G. Pasolini et al., 2020. Crowd-Based Cognitive Perception of the Physical World: Towards the Internet of Senses, Sensors 2020, 20(9):2437, pp. 1-18.
[11] R. D'Errico et al., 2020. Reconfigurable and Focused Surfaces and Channel Characterization at mmWave. CA15104 TD(20)12035 Louvain-la-Neuve, Belgium January 27-29, 2020.