

Towards a Steerable Optical Wireless Integrated Sensing and Communication System

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Abstract— This paper presents a potential beamsteered 5G/6G Compliant Optical Wireless Communication cell free network solution for facilitating longer propagation distances, wider coverage areas and more accurate and reliable indoor localization, which is realised using a combination of VCSELs Infra-red source and Integrated Photonic Processors. The intended use case is smart transportation of materials in Industry 4.0 factories.

Keywords— 5G/6G IR OWC Cell Free Network, DToA, RSS and AoA Localisation, Smart Transportation in Industry 4.0.

I. INTRODUCTION

Empowering an IR OWC network with beamsteering functionality and making it capable of covering a total field of emission angles as wide as 180 degrees could in the ideal case make optical wireless communication (OWC) networks a more commercially attractive, sustainable and energy efficient solution for use in indoor environments. Since however it is hard to correlate the phases of the individual vertical cavity surface-emitting lasers (VCSELs) and ensure coherence between them by using an injection locking scheme, an alternative operation mode should be established in order to retain the possibility for wide angular coverage. An alternative operation mode could be based on the physical orientation of the VCSELs into different directions covering together the total target field of emission angles, and on the use of an electrical (beam) switching circuit that receives the input data signal and directs it for optical modulation and optical beam emission to only one of the VCSELs, depending on the angular sector, where the target user will reside in.

An alternative, forward looking solution based on the use of an optical phased array (OPA) with a Blass-matrix-based distribution network and a linear array of grating couplers acting as optical antennas is an alternative approach, which can be developed in the form of a photonic integrated circuit (PIC), and tested. This OPA could form 4 independent narrow beams, and will have the

possibility for continuous 1D steering of those beams (multi-beam operation) over a total field of emission angles up to 45°, or even the possibility for continuous 2D steering if wavelength tuning of the laser sources can also be employed. Given the passive and all-optical nature of the OPA, the specific system could be used in combination with a fiber extension link, demonstrating the possibility to serve a remotely located network of access points (APs) equipped with this kind of OPA.

Improvements are expected in the coverage area, throughput to and from (Downlink and Uplink) the User Equipment (UE) as well as the handover time from cell to cell.

The combination of these technologies with a traditional 5G microwave (usually at 3.5 GHz (n78 band) network, which is adapted to operate as an OWC with 1560 nm wavelength, could be a big step forward to the integration of OWC and location-based services as part of the 6G and industry 4.0 use-cases, since OWC-based systems offer unlicensed, interference-free spectrum by utilizing the visible and invisible light spectrum. A further motivation is to test the benefits of the cell-free 5G network operating at the optical domain rather than in the traditional microwave domain.

Inherently, OWC systems enhance security and privacy in communications, making them suitable for a variety of applications, including Industry 4.0.

II. SYSTEM ARCHITECTURE OVERVIEW

A. Building Blocks (Core, CU, DU, RU, OWC and UE) Description

A basic cell-free 5G network consists of two APs, or remote units (RUs), that are connected to a single central processor unit called Network In a Box (NIB), as shown in Fig. 1. The NIB includes a 5G core (NgCore), a Control Unit (CU) and a Distributed Unit (DU) protocol stack installed on a

high-end server, which is connected to the two RU via the ORAN PHY Split option 7.2.

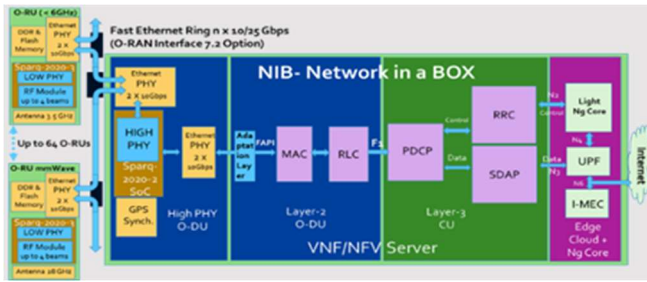


Figure 1: Network In a Box connected to two RUs

B. OWC System Design and Implementation

VCSELs are the preferred light source for OWC (LiFi) systems due to their high modulation bandwidth, which enables high-speed data transmission, while their low power consumption and high efficiency make them energy-efficient. VCSELs are also compact and inexpensive to manufacture, facilitating their integration into various devices. Additionally, their eye-safe operation and ability to form 2D arrays make them suitable for a wide range of applications, from indoor communication to outdoor wireless networks, as shown in Fig. 2.

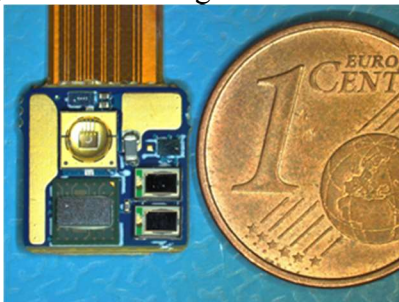


Figure 2: Current optical antenna used in cell-based LiFi systems. (4x4 VCSEL array)

The light source will be selected in order to match the minimum 64° field-of-view (FOV) in emission. At least 2 VCSELs will be used to have a symmetric pattern of light and optimize performances. A 2x1 VCSEL configuration will also allow to potentially reuse the design in future beamsteering integrations. The VCSELs will utilize the driver by the Oledcomm “Keren” chipset for preamplification, amplification and automatic gain control implementation.

PIN photodiodes are well-suited for optical wireless communication due to their good balance between sensitivity, noise and response time. They offer a good compromise between performance and cost,

making them a popular choice for LiFi systems. They are relatively simple to manufacture and operate, contributing to their widespread use in various optical communication applications. Hamamatsu photodiodes will be used, which offer the best compromise between: Size of sensing area; Sensitivity at 1560 nm; Bandwidth; Thermal performances.

C. Cell Free OWC Networks

Although OWC networks are inherently cell-free within for example a cluster of 6 OWC photonic antennas controlled by a single OWC APs to typically support a 4x5 meters coverage area, handover is required between clusters of 6 OWC photonic antennas controlled by different OWC APs, see Fig. 3.

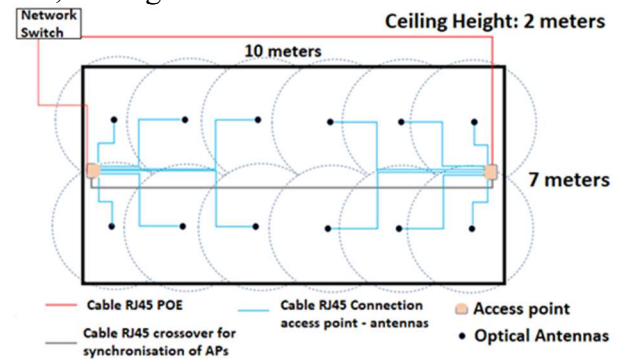


Figure 3: OWC Network with 2 access points.

Clearly this poses a challenge for a large factory such as Bosch’s I4.0 factory in Feuerbach (The Bosch plant in Feuerbach – where tradition meets high-tech - Bosch Media Service (bosch-presse.de)) with a floor space area of 109,100 m², since not only would it require 5455 OWC AP clusters, but also the mobility of user equipment within the coverage area would incur excessive number of handovers and signalling.

So, the first motivation is to design a cell-free network where handover between AP clusters are no longer needed for mobile users. This paves the way towards a beamsteered OWC system, which will ultimately produce much wider access angles, thus requiring much fewer OWC APs. Increasing the radius by a factor of 4 with a field of emission angle of 70° provides a coverage area from one access point of 16x20 m = 320 m² which would require 340 OWC AP clusters for a factory with a floor space area of 109,100 m². This is much more commercially viable.

D. Adaptation of the PHY Air Interface

Beamsteering and beamforming adaptation of the PHY air interface is achieved by using innovative Integrated Photonic Processor (IPP), which can be configured to produce an up/down converter, frequency conversion, filtering, beam forming, tuneable true time delay and splitting and combining for near IR OWC energy efficient radio signal distribution. It supplements the IPPs for the near IR OWC communication systems with High Speed Photo Detectors and Transducers (HSPT), so that they can be interfaced to the Optical VCSEL Phase Array Emitters/Sensors. The merits of processing wireless communication signals with microwave photonics in microwave domain is because everything is small, fast and light weight enough for integration into smart phones and radio access nodes, where processing can be performed on extremely large bandwidths with extremely low losses.

E. IR Beam-switching

The IR beam-switching OWC system comprises of 4 VCSELs with four different (minimally overlapping) orientations, as shown in Fig 4. Given that each VCSEL can support a data rate of 1 Gb/s up to 5 m with a total divergence angle of 25° or a data rate of 3 Gb/s up to 5 m with a total divergence angle of 15° , this quad VCSEL array setup is thus capable of extending the angular coverage of the system up to 60° - 100° , and will still represent a commercially attractive, sustainable and energy efficient 1550 nm solution for use in indoor environments. It is noted that in the uplink part, a corresponding set of 4 photodiodes (PDs) will have the same orientations as the 4 VCSELs for light detection from the user UE.

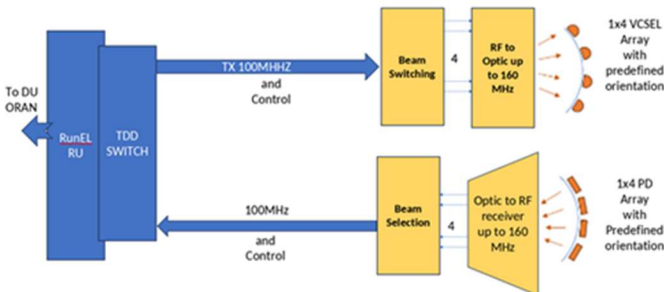


Figure 4: OWC beam switching circuit case

F. IR Beamsteering – Optical Phased Array Solution

OWC in the form of free-space optical (FSO) links have been gaining attraction partly due to their inherent nature of acting as a wireless fibre

extender within communication networks, providing the ability to serve remote nodes while at the same time alleviating the need for power-hungry optical-electrical and vice versa conversion stages, as well as the need of cabling and installation costs. Within that context, optical beamsteering by means of optical phased arrays (OPAs) emerges as a promising technique combining the well-established advantages of standard beamforming in the electrical domain, while concurrently enabling powerful parallel applications such as localization, LIDAR etc in the same communication link [RAP24]. Here we propose a disruptive photonic integrated circuit (PIC) comprising an optical beamforming network (OBFN) coupled with an OPA acting as the optical emission unit.

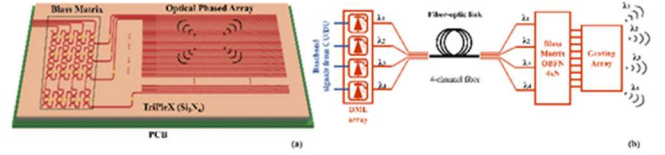


Figure 5: (a) Artistic illustration of the proposed OPA PIC, (b) Schematic representation of the proposed system.

Figure 5(a) depicts an artistic illustration of the PIC under consideration. The photonic integration platform of the node is the proprietary silicon nitride platform of LioniX International known as TriPleX [ROE18], offering ultra-low propagation losses enabling us to monolithically integrate the OBFN and the OPA, as well as to scale-up the PIC's dimensions providing finer tuning and thus higher scanning resolution. The OBFN is based on the Bliss-Matrix architecture [TSO18] with dimensions $4 \times N$. This architecture, usually employed in mmWave OBFNs, allows for the accommodation of multi-beam operation with four independent optical beams, to be emitted by the N optical antenna elements (OAEs) of the OPA. The OAEs will be grating couplers in a linear array configuration, which enable the formation of a well-defined, nearly Gaussian beam profile without need for additional use of micro-optics elements such as lenses.

Figure 5(b) demonstrates the integration of the proposed PIC node in the system. In the uplink direction, an optical fibre transmission part comprising four direct modulation lasers (DMLs) will be used for light generation and modulation from four independent baseband signals of 100 MHz bandwidth coming from the CU/DU. The four signals will be transmitted over a 4-lane SMF

bundle to the network access point, where the OPA will be responsible for the formation, steering and emission of four independent optical beams without any opto-electro-optical transition. The downlink direction will be based on the same schematic depicted in Figure 4.

G. Photonic System Packaging

The packaging approach prioritizes the simplification of the process while ensuring cost-effectiveness for high-volume industrial manufacturing. This approach entails the implementation of integration and packaging methodologies, which are designed to ensure compatibility between individual components and units. These methodologies address the optical, electrical, mechanical, and thermal properties of the components. Furthermore, the physical dimensions and geometries of the combined photonics platforms are considered for the purpose of seamless integration from all perspectives.

A comprehensive process flow for the execution of reliable assembly and packaging procedures, including automated post-packaging test methods and tools, ensures efficient integration of photonic-electronic co-assemblies.

A three-dimensional mechanical model of the system, in conjunction with thermal simulations, facilitates the evaluation of the assembly feasibility and the thermodynamic behavior of the system. These simulations facilitate the identification of local hotspots and the subsequent stress, thereby supporting the optimization of the integration concept and the development of strategies for thermal management. The creation of thermal paths for electronics and photonic chips involves the utilization of copper blocks for heat spread, in conjunction with active cooling methods or other heat dissipation elements. This approach constitutes the thermal management solution for the system.

The model enables the analysis of subsequent assembly steps, including handling feasibility, alignment mark positioning, electrical and optical connection feasibility verification, vertical profile evaluation, and epoxy resin dispensing. The knowledge gained from these analyses is then used to refine the packaging process, ensuring continuous optimization and alignment with system requirements.

III. USER EQUIPMENT LOCALIZATION METHODS

A. Time (Difference) of Arrival and Power (Difference) of Arrival based techniques

OWC system will be supplemented with a sub-cm optical wireless positioning (OWP) and sensing solution, whose accuracy has already been proven at 3.5 GHz to be within 3 - 4 cm, to see if increased accuracy and reliability can be obtained by operating at beamsteered IR frequencies.

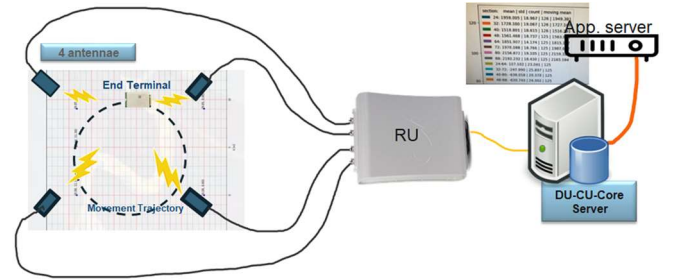


Figure 6: System Diagram for TDoA

Reconfiguration of the OWC 5G Network to have OWC Tx at the UE and four OWC Rx at the TU, as shown in Fig 6, allows highly accurate time difference of arrival (TDoA) relative distance measurements to be performed to produce location using hyperbolic trilateration process.

B. Received Signal Strength based techniques

RSS-based positioning is estimated, from the RSS of signals coming from different Access Points, to produce the absolute distances between these APs and the UE using a known path loss model. Trilateration is then used to determine the unique point in space located at these estimated absolute distances from the APs.

C. Beamsteering-Based Techniques

In addition to TDoA and RSS techniques, an OWP solution based on the possibility of changing the orientation of optical sources using the beamsteering techniques described above will be developed. Already validated for 2D positioning [CHA25], this solution has the advantage of requiring only a single optical source on the AP side - albeit a steerable one - and a single PD on the UE side to estimate the latter's position, unlike RSS and TDoA solutions, which generally require several optical sources and/or PDs.

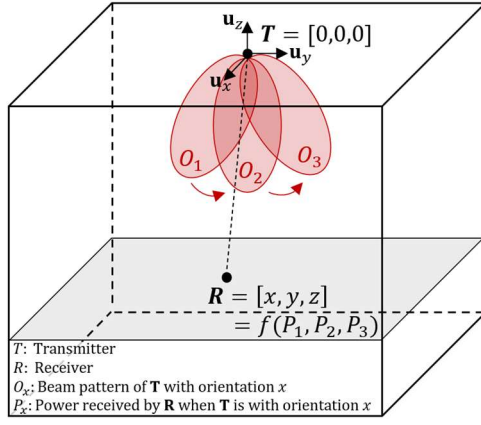


Figure 7: Working principles of the proposed beamsteering-based OWP solution.

Fig 7 illustrates the main working principles of this beamsteering-based technique: a steerable IR optical source, of known beam pattern, is placed at point T and emits a signal (e.g. a data signal) in at least three consecutive orientations O_1 , O_2 and O_3 . The UE, located at point T , collects the resulting signals and computes their RSS P_1 , P_2 and P_3 , from which it can deduce its 2D location. Assuming the source can also change its pattern, which will be possible using the proposed beamsteering-solution previously described, 3D positioning will be possible using a similar procedure.

D. Fingerprinting techniques

One of the prominent methods for localization in OWC systems is RSS-based fingerprinting, which uses the RSS at various points in an environment to create a “fingerprint” of the location [HE16].

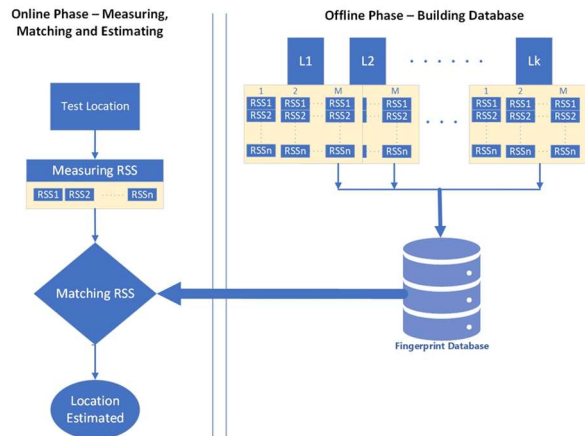


Figure 8: Two Phase fingerprinting Process

Fingerprinting is a two-stage localization technique used to estimate a device's position based on previously collected signal data. The technique relies on building a database of signal characteristics (RSS in this case) at various known

locations during an offline phase. In the online phase, the device's RSS measurements are matched against the database to estimate its location. RSS fingerprinting is widely used in indoor environments where multipath fading and NLOS conditions make other localization techniques, such as trilateration, less effective.

In OWC systems, fingerprinting typically involves collecting RSS data from light sources (e.g., LEDs) at different positions in the area of interest. Given that light propagation is typically LOS in OWC systems, RSS measurements tend to be more stable than in RF systems, where multipath fading and interference are more pronounced. The RSS fingerprinting process in OWC systems involves two main phases: the offline phase (training) and the online phase (testing or real-time localization) as shown in Fig 8.

E. Localisation Fusion

Measuring location using both the TDoA and RSS from uplink transmissions at the OWC antennas in Cellfree OWC network requires OWC antennas to simultaneously make measurements from a single transmission at from the UE. This avoids use of extrapolation to counter measurements of distance at different times in order to time align measurements established from asynchronous sensors [Meu22]. Simultaneous measurements using both the TDoA and RSS allows more accurate and reliable estimates of locations to be obtained.

IV. USE CASES

A. Smart Transportation Vehicles

This use case describes a typical driverless transport system (DTS) scenario in production environments. Two important functions of DTS often referred to as automated guided vehicles (AGV):

- Localization of an AGV in different scenarios with high requirements on accuracy for the localization ($< 1\text{cm}$),
- Video processing offloading from an AGV camera to the neighbour edge computing node with high requirements on data rate ($> 500\text{Mbps}$).

Automated factories whose building with large thousands of m^2 manufacturing space would benefit from a private 5G/6G campus network, facilitating state-of-the-art Smart Logistics and Smart Manufacturing features:

- Assets Tracking
- Autonomous driving of materials by Automated guided vehicles (AGV)
- XR-based operator assistance

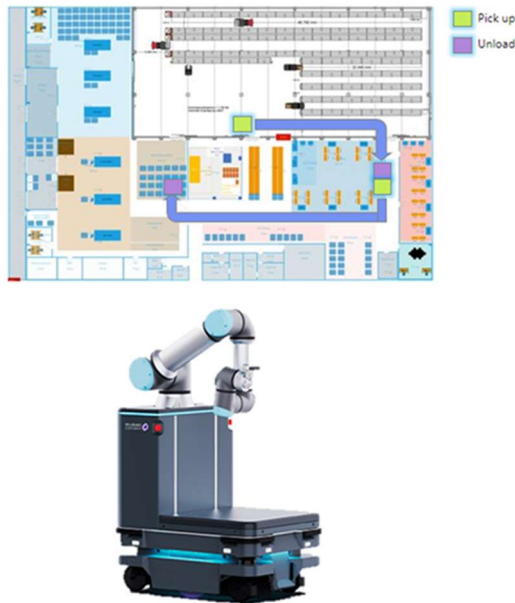


Figure 9: Autonomous driving of materials

Currently the 5G/6G private network uses licensed 3.7 GHz spectrum, which requires expensive purchase of a license. One of the use cases “Autonomous driving of materials” is shown in Fig 9.

Autonomous driving of materials highlights:

- Drive material from a defined pick-up point to a defined unload point using a CARY robot.
- There can be multiple pick up and unload points.
- Operators and robots acting in the same working area.
- Operators working in a 1 shift model. If possible, robot can also use time slots for 2nd and 3rd shift.
- Material cart size fixed to be 600 x 600 mm. CARY robot has 5G Modem, allowing tracking and having them at the right point in time at the right place.

Main challenges are ultra-high bandwidth (up to 3 Gbps) for video processing offloading

- Ultra-high precision (1 cm and 1 degree) positioning for AGVs
- 3D localization, i.e., position estimation of AGV, in radio multi-path shop floor environments

- Position estimation with limited number of reference points
- Reliable connection to AGV (see Mobile robots use-case in 3GPP)

Thus, efficient operating factories require Industry 4.0 facilities where the new 5G/6G technology could be evaluated and further integrated in a real operational process.

V. CONCLUSIONS

This paper presents a beamsteered 5G/6G Compliant Optical Wireless Communication cell free network solution for facilitating longer propagation distances, wider coverage areas and more accurate and reliable indoor localization. Realising this system using a combination of VCSELs Infra-red source and Integrated Photonic Processors means that EM radiation, interference and energy consumption will be considerably reduced, and mobile access to users within buildings improved by not incurring interference with the wider 6G mobile network, thus producing a more sustainable solution.

ACKNOWLEDGMENT

The authors gratefully acknowledge support of EU Horizon 2020 Research Project OPTI-6G (OPTICAL 6G CELL FREE NETWORKS) No 101139292 and the TERA6G (Terahertz integrated systems enabling 6G Terabit-per-second ultra-massive MIMO wireless networks) No 101096949.

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