The optical spectrum and Tb/s wireless systems in the 6G era

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• TOWS 6G Vision
• Industrial eco system
• TOWS project
• 4G, 5G and 6G
• Use Cases
• Highlights
  • Hardware
  • Systems
  • Architecture
  • Demos
• Future directions
Terabit Bidirectional Multi-user Optical Wireless System (TOWS) for 6G LiFi

**Vision**

Our vision is to develop and experimentally demonstrate multiuser Terabit/s optical wireless systems that offer capacities at least two orders of magnitude higher than the current planned 5G optical and radio wireless systems, with a roadmap to wireless systems that can offer up to four orders of magnitude higher capacity.

*First, UK 6G project; paradigm shift from radio to optical, indoor*

April 2019 – March 2024, £6.6m project
<table>
<thead>
<tr>
<th>Vendors</th>
<th>Devices</th>
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<td>IQE</td>
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<td>Compound Semiconductor Technologies</td>
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<td>Optical Systems</td>
<td>ADVA Optical Networking</td>
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<td>orange™</td>
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<td>Deutsche Telekom</td>
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<td>Microsoft</td>
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<td>Software, manufacturing</td>
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<td>Babcock</td>
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<td>Airbus Group</td>
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Drivers and future directions

- Internet traffic is projected to grow by factors of 30x and 1000x in 10 and 20 years respectively.

- Mobile data is the fastest growing traffic strand, currently growing at 60% per year leading to a projected growth of over 10,000x in 20 years.

- Despite the tremendous improvements due to the small cell concept and the allocation of new radio frequency (RF) spectrum in 5G, it is inevitable that the RF part of the electromagnetic spectrum will not be sufficient to drive the 4th industrial revolution.

- This highlights the need for a step change in approach via new technologies that are able to provide communication efficiently at parts of the spectrum other than the 100GHz of RF spectrum currently in use.

- Current estimates are that 80% of all mobile connections originate and terminate indoors.

- A potential disruptive solution is optical wireless (OW) communication.
TOWS project

Investigators, Strategic Advisory Board and end users extract requirements and constraints

Architecture, WP4 Multi-user system access architecture, WP5 Resource Allocation, WP6 Virtualisation, SDN management and cooperation

Thrust 1: Innovative Hardware
Thrust 2: Mobile Multiuser Architectures
Thrust 3: Enabling Algorithms for Channel Agility, Adaptation and Resilience
Thrust 4: Demonstration

Demonstration WP10: Drawing together the three Co-Creation thrusts through modelling tool; and hardware demonstrators
## Mobile Radio and Optical Wireless Data Rates

<table>
<thead>
<tr>
<th>Mobile base station</th>
<th>Data rate</th>
<th>Mobility</th>
</tr>
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<tbody>
<tr>
<td>4G</td>
<td>100Mb/s – 300Mb/s</td>
<td>High</td>
</tr>
<tr>
<td>5G</td>
<td>10Gb/s</td>
<td>Small Cells</td>
</tr>
<tr>
<td>IEEE 802.11 bb</td>
<td>10Gb/s peak</td>
<td>WiFi size cells</td>
</tr>
<tr>
<td>(optical wireless)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE 802.15.13</td>
<td>10Gb/s (July 2019)</td>
<td>LoS, 200m</td>
</tr>
<tr>
<td>(Multi-Gigabit/s</td>
<td></td>
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<tr>
<td>Optical Wireless</td>
<td></td>
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</tr>
<tr>
<td>Communications)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE 802.15.7r1</td>
<td>100 Mb/s</td>
<td>High</td>
</tr>
<tr>
<td>(Optical Camera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication (OCC))</td>
<td></td>
<td></td>
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<tr>
<td>Experimental Optical</td>
<td>40Gb/s</td>
<td>Beam steering</td>
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<tr>
<td>Wireless</td>
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<tr>
<td>TOWS</td>
<td>1Tb/s – 10Tb/s</td>
<td>Indoor mobility, 50m² per access point; 2.5Gb/s - 50Gb/s per user</td>
</tr>
</tbody>
</table>

- **TOWS BBC use case:**
  - Studio **22m x 14m or 30m x 33m**
  - Uncompressed UHDTV, **23Gb/s per camera**
  - 12 to 20 cameras in studio; **up to 460Gb/s**; 4-5 cameras used sometimes)
TOWS architecture and sub-systems
TOWS architecture and sub-systems

Indoor

In cabin

In data centre

Multiple access

Integration

Transmitter module

Angle diversity receiver

Surface relief and polarisation pinned VCSELs for beam and spectral control
Hardware: Current studies

Current work:
- Transmitter and Receiver optics
- room coverage, AP distribution
- high speed VCSEL-based links
- beam steering concepts
- system implications
Hardware: Transmitter optics

- work on the design of Tx optics system for TOWS system:
  - 1 m² covered with a 5 × 5 VCSEL array
  - beam homogenisation at the floor plane → uniform SNR
  - minimise beam interference (direct path)
  - eye safety considerations → formation of high-capacity communication cells

- 5 × 5 VCSEL array
- beam homogenisation system
- floor intensity
- ~ 86% intensity uniformity
Hardware: Laser safety

Highlights:

A generalized framework for laser safety analysis has been developed where the maximum permissible transmit power of a laser source ensuring both skin and eye safety, is derived for various cases including:

1. Single mode Gaussian/non-Gaussian beams
2. Multi-mode beams (through measurements)
   - Hermitte-Gaussian beam
   - Laguerre-Gaussian beam
3. Laser with lens
   - System of lenses
   - Thin lens
4. Laser with diffuser
   - Lambertian pattern diffusers
   - Uniform pattern diffusers
5. Laser array
   - Laser array with a collimated beam
   - Laser array with diverged beams

Publications:
Hardware: Room coverage

- application in the room for coverage \((3 \times 3 \, \text{m}^2)\)

→ distribution of access points (APs)

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameter</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Access Point</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Transmitter/ AP</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Covered area %</td>
<td>91%</td>
<td>92%</td>
</tr>
</tbody>
</table>

Alternative shaping of output beam

single VCSEL beam shaping
System: Terabit optical wireless system

Highlights:

- A novel double tier access point (AP) architecture based on **array of arrays** of vertical cavity surface emitting lasers (VCSELs) is proposed.
- The AP covers the entire indoor area.
- The AP provides an aggregate data rate beyond **1 Tb/s** (at least **10 Gb/s per beam**).
- The inter-beam interference is minimized.
- This design supports multi-user access.
- This design is subject to the optical power emission limit for VCSELs due to eye safety.

Publications:
System: Spatial distribution of the data rate over the coverage area

System parameters: Link distance: 3 m; Number of VCSELs: 225; VCSEL output power: 10 mW; VCSEL bandwidth: 10 GHz; Detector effective area: 2 cm²

Individual beams:
Data rates of 10 to 20 Gb/s are achieved at the beam spot centres.
The AP delivers an aggregate data rate of beyond $225 \times 10 \text{ Gb/s} = 2.25 \text{Tb/s}$.

Static clusters:
Clustering helps to improve the spot-edge rate performance. Each cluster is composed of a number of neighbouring beam spots.

Publications:
System: Terabit optical wireless backhaul

**Highlights:**
- A MIMO optical wireless backhaul system using VCSEL arrays is proposed.
- A $25 \times 25$ system using $5 \times 5$ arrays achieves an aggregate data rate of more than 1 Tb/s.

**System parameters:**
- Link distance: 2 m
- VCSEL output power: 1 mW
- VCSEL bandwidth: 20 GHz
- Effective area per detector: 0.5 cm$^2$

$w_0$ is the effective beam waist radius.

**Perfect Alignment**

**Misalignment**

for $25 \times 25$ MIMO and $w_0 = 100 \,\mu m$

**Publications:**
System: High-speed operation

- work on advanced modulation formats and equalization methods

→ new equalizer structure for CAP-based optical links: CAP equalizer
→ demonstrated in VCSEL-based MMF link: 124 Gb/s achieved with 25 GHz VCSEL
→ low complexity implementation – similar to conventional FFE/DFEs

→ similar concepts to be applied to TOWS systems to improve link capacity

X. Dong, et al., JLT, vol. 37, pp. 5937-5944, 2019
X. Dong, et al., in ECOC, pp. 1-3, paper P.20, 2019
Architecture: Resource allocation

- \( SIR_{u,r}^{c,a,\lambda} = \frac{\text{Signal}}{\text{Interference + Noise}} \)
- Signal: \( S_i^{u,r} = (R P_t^{c,a,\lambda} h_{u,r}^{c,a,\lambda})^2 \)
- The preamplifier noise: \( \sigma_{RX} = N_{pr} B_e \)
- The background light shot noise: \( \sigma_{cc,b,\lambda} = 2e (R P_t^{c,c,b,\lambda} h_{u,r}^{c,c,b,\lambda}) B_o B_e \)
- \( SIR_{u,r}^{c,a,\lambda} = \frac{S_i^{u,r} - \sigma_{cc,b,\lambda}}{\sum_{c \in C} \sum_{b \in A} \sum_{\lambda \in W} \sum_{r \in B} S_i^{u,r} - \sigma_{cc,b,\lambda}} + \sigma_{RX} \)

The MILP model is subject to:

- \( \sum_{u \in U} \sum_{r \in B} S_i^{u,r} \leq 1 \quad \forall c \in C, \forall a \in A, \forall \lambda \in W \)  
  (To ensure that a wavelength belonging to an AP is only allocated once)
- \( \sum_{c \in C} \sum_{a \in A} \sum_{\lambda \in W} \sum_{r \in B} S_i^{u,r} = 1 \quad \forall u \in U \)  
  (To ensure all users are assigned to one cell unit, access point, one wavelength and one branch)
- \( SIR_{u,r}^{c,a,\lambda} \geq 10^{\frac{36}{10}} \quad \forall u \in U, \forall c \in C, \forall a \in A, \forall \lambda \in W, \forall r \in B \)  
  (To ensure the SINR of each user does not go below 15.6 dB)

Multiuser architectures

Optical Cell Formation
- Full connectivity design
- Network centric design
- User centric design: optimal and sub optimal UC approach

Interference Management
- Precoding schemes: ZF, MSE, MMSE and RS
- Power control and Blind schemes: NOMA and BIA
- Hybrid schemes: HRS, BIA-RS, BIA-NOMA and H-BIA

Cell formation

Hybrid schemes
Multiuser architectures

BBC studio

- Each camera equipped with transmitter using VCSEL covers an area that can reach up to 1.45 m x 1.45 m at 11m distance.

Fig. 1. A use case.

Fig. 2. SE vs distance.
Architecture: Backhaul fibre network

• Purpose:
  • Access Point (AP) to AP wired links within a room for **device to device** communication
  • Room to room and floor to floor links for user Mobility and for Aggregating processing capacity from user devices, IoT devices and distributed servers

• Proposed PON-based Networks:
  • WDM-TDM architecture (uses AWGRs and tunable lasers)
  • Point-to-Point single wavelength architecture (use APs for routing)
Architecture: Backhaul fibre network modelling

• Developed a MILP Model to Optimise Flow Scheduling and Routing between APs to evaluate the impact of network topology on the performance and energy efficiency
• Comparison with Fat-tree and Spine-leaf
• MILP Objective: Minimise the energy consumption (E) or the latest completion time (M) of data transfer

\[
\min \left[ E + Q \sum_{s,d \in R, t \in T, s \neq d} (t \delta_{sd,t}) \right], \quad \min \left[ M + Q \sum_{s,d \in R, t \in T, s \neq d} (t \delta_{sd,t}) \right].
\]

• Under several constraints (e.g. flow conservation, traffic scheduling, completion time calculation)

\[
\sum_{v \in G_u} \chi_{uuvwt} - \sum_{v \in G_u} \chi_{vuvwt} = \begin{cases} 
\delta_{sd,t} & u = s \\
-\delta_{sd,t} & u = d \\
0 & \text{otherwise},
\end{cases}
\]

\[
\forall s, d \in R, s \neq d, u \in G, w \in W, t \in T.
\]

\[
\sum_{t \in T} \delta_{sd,t} = \Delta_{sd}; \forall s, d \in R, s \neq d
\]
For the WDM-TDM architecture, completion time is reduced by about 50% compared to remaining networks while reducing the energy consumption by up to about 88%.

Future work considers AP-AWGR wireless links, designing room to room, floor to floor interconnection, and optimizing workloads placement and users mobility.
Architecture: Cloud-Fog Processing

Objective: \( \text{Minimize } \sum_{n \in PN} P_n + \sum_{n \in PN} P_n \)

where \( P_n \) is the processing power consumption, given by
\[
P_n = \sum_{k \in K} X_{kn} E_n \quad \forall \ n \in PN,
\]
\[
E_n = \max \text{ power consumption} \quad \text{max processing capacity}
\]

and \( P_n \) is the networking power consumption, given by
\[
P_n = \sum_{k \in K} L_{kns} \psi_n \quad \forall \ n \in PN, \ s \in SN,
\]
\[
L_{kns} = F_{k} \delta_{kn} \quad \forall \ k \in K, s \in SN, n \in PN
\]

\[
\psi_n = \max \text{ power consumption} \quad \text{max traffic capacity}
\]

The model is subject to the following constraints:

1- Processing allocation \( \alpha \ X_{kn} \geq \delta_{kn} \quad \forall \ k \in K, n \in PN \)
\( \alpha \ X_{kn} \leq \alpha \ \delta_{kn} \quad \forall \ k \in K, n \in PN \)

2- Single allocation (no splitting) \( \sum_{n \in PN} \delta_{kn} = 1 \quad \forall \ k \in K \)

3- Processing capacity \( \sum_{k \in K} X_{kn} \leq C_n \quad \forall \ n \in PN \)

4- Link capacity \( \sum_{k \in K} \sum_{s \in SN} \sum_{d \in PN} X_{ijs} \leq L_{ij} \quad \forall \ i \in N, j \in N \text{ and } i \neq j \)

5- Flow conservation \( \sum_{j \in N_{m_i}} x_{ijs}^{k_a} = \sum_{i \in N_{m_j}} x_{jds}^{k_a} = \left\{ \begin{array}{ll} L_{k_a} & \text{if } i = s \text{ and } i = d \text{ otherwise} \\ -L_{k_a} & \text{if } i = d \end{array} \right. \quad \forall \ k \in K, s \in SN, d \in PN, i, j \in N \)

Demos: BBC strictly come dancing
Long Term Vision for 6G

- **Wireless Capacities** 2 to 4 orders of magnitude higher than 5G (Tb/s)

- **Latencies** 1 to 2 orders of magnitude lower than 5G (μs), autonomous systems

- **Intelligence everywhere** (machine learning and AI)

- **Planet wide coverage** (Hetnets and low orbit satellites)


Publications: Journals


Publications: Conferences


Publications: Conferences


73. A Novel Linearization Method for Optical Transmitters Based on Directly-Modulated Lasers, Nikos Bamiedakis; David Cunningham; Richard Penty; OFC 2021


Publications: Invited Talks

85. “A new equalizer structure for high-speed optical links based on carrierless amplitude and phase modulation”, Nikos Bamiedakis, Xiaohe Dong, David G Cunningham, Richard V Penty, Ian H White, 2020 22nd International Conference on Transparent Optical Networks (ICTON), pp. 1-7