Mitigation of atmospheric turbulence effect using Photonic Integrated Circuits (PIC) for optical communication

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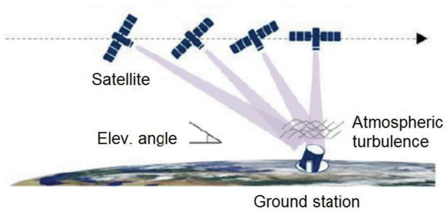
Context: Optical Communication

Issue: Increasing needs for satellite-to-ground communication with radio-frequency bandwidth saturation.

➔ **Solution:** Free Space Optical links (FSO) with Single Mode Fibre (SMF) coupling enable 10 Gbps.

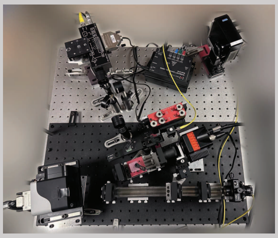


Issue: SMF coupling with atmospheric turbulence effects.

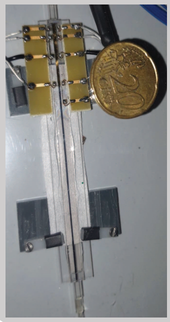
Solution: Adaptive Optics (AO) vs PIC

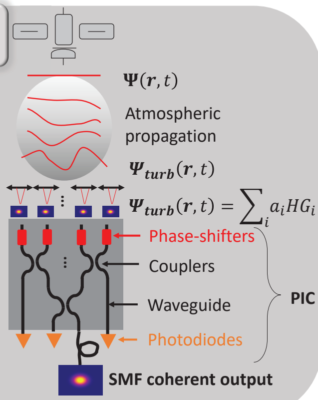
AO limits:

- Bulk optics,
- Robustness : lot of mechanical parts,
- Implementation complexity.



New concept: Coherent recombination using PIC.



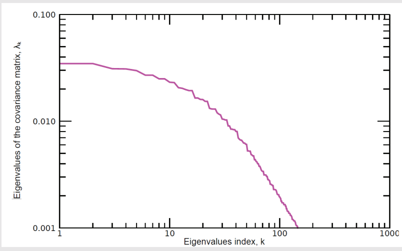


Spatial and Temporal properties

Principle: Perturbed fields modal decomposition supported by Gaussian modes to be coherently recombined using output intensity measurements [1][2].

PIC inputs turbulent energy distribution after modal decomposition [2]

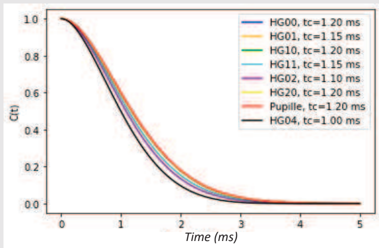
$$< a_i \times a_j^* > = \int\int Hg_i(\mathbf{r}) HG_j(\mathbf{r'}) P(\mathbf{r}) P(\mathbf{r'}) < \Psi_{turb}(\mathbf{r}) \Psi_{turb}(\mathbf{r'})^* > d\mathbf{r} d\mathbf{r'}$$



100 modes decomposition required for a 30° satellite elevation [2].

Temporal evolution of PIC inputs after modal decomposition

$$C_i(\tau; r_0, V) = \int_\rho \prod_k \left(B_\Psi \left(\frac{\rho - \tau V(k)}{r_0(k)} \right) \right) \times [(P.HG_i) \otimes (P.HG_i)](\rho) d\rho$$



Temporal evolution of 1 ms for a 30° satellite elevation [3].

PIC control?

Non-linear relation between Phase-shifters space and intensity measurements

- Gradient descent :
  - Stochastic: SPGD, D-SPGD [4],
  - Sequential modulation [5],
  - Multi-frequential modulation [6].

➔ Slow convergence, high modulation bandwidth required.

- Non-linear algorithm:
  - Artificial intelligence [7],
  - Nelder-Mead [8].

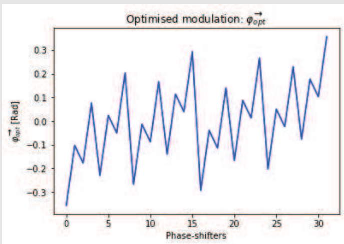
➔ Not accurate near convergence.

Needs for a specific control algorithm using relatively low modulation bandwidth and robust to noise.
➔ Spatial modulation: Spatial diversity, all outputs.

Spatial Diversity Control Algorithm E2E Simulation

Spatial diversity

- Spatial modulation applied on all phase-shifters at the same time,



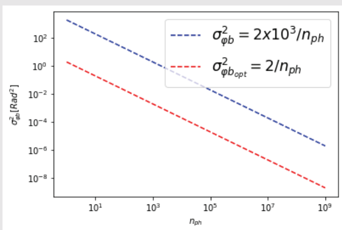
- All output measurements vector $\vec{S}$
- Residual phase linearized model:

$$\overrightarrow{\varphi_{res}} = \boldsymbol{M}^{\dagger} \vec{S}$$

Photon noise propagation optimisation

$\overrightarrow{\delta\varphi}$ optimisation to minimise photon noise propagation

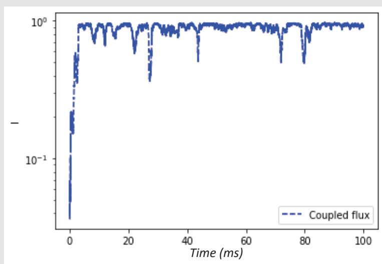
$$\sigma^2 \varphi_b = \frac{tr(\boldsymbol{M_u^{\dagger}} \boldsymbol{M_u^{\dagger t}})}{n_{ph}(N-1)} \approx \frac{2}{n_{ph}}$$



- $\overrightarrow{\delta\varphi_{opt}}$ enables theoretical minimum noise propagation. Results obtained both by numerical optimisation & analytical solution,
- Algorithm still valid out of linearised working point.

E2E modelling

- 30° elevation, $\frac{D}{r_0} = 5, \sigma_\chi^2 = 0.085$,
- 32-inputs PIC,
- $f_{corr} = 10\ kHz, f_{mod} = 50\ kHz$,
- Closed loop integrator.



Conclusions and Perspectives

Conclusions

- PIC inputs temporal evolution of 1 ms,
- Spatial diversity algorithm validated by E2E simulation,
- Modulation optimised to reach theoretical minimum photon noise propagation.

Perspectives

- Experimental tests,
- Other PIC architecture developments,
- PIC technology choices,
- Control algorithm optimisation.

Bibliography

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