POLITECNICO DI MILANO

PhD in INGEGNERIA DELL'INFORMAZIONE / INFORMATION TECHNOLOGY - 41st cycle

Research Area n. 4 - Telecommunications

BORSE TEF Research Field: MAXIMIZING PHOTON INFORMATION EFFICIENCY: TOWARD QUANTUM-LIMITED OPTICAL COMMUNICATION SYSTEMS

Monthly net income of PhDscholarship (max 36 months)
1800.0 In case of a change of the welfare rates during the three-year period, the amount could be modified.

Context of the research activity	
Motivation and objectives of the research in this field	The growing demand for high-capacity, long-distance communication systems, particularly in space and deep-space missions, has highlighted the limitations of existing radio-frequency and optical technologies. While laser-based optical communication provides substantial advantages in bandwidth and noise resilience compared to radio systems, current detection techniques impose fundamental constraints on efficiency. In particular, for coherent detection, the standard approach for high-speed optical links, is limited in the amount of information that can be reliably transmitted per photon due to the quantum nature of light. These limitations become increasingly severe in power-constrained and high-loss environments, where photon availability is extremely limited. Recent advances in single-photon detectors and timing-based modulation schemes, such as pulse-position modulation, have demonstrated the potential to significantly exceed the photon information efficiency achievable with coherent detection. However, despite promising experimental results, existing approaches remain far from the ultimate limits imposed by quantum mechanics, and their performance across a wide range of spectral efficiencies is not yet fully understood. This motivates the need for new transmission, detection, and decoding strategies that more effectively exploit the

	discrete nature of light to approach quantum-limited communication performance. The primary objective of this research is to develop photon-efficient optical communication strategies that maximize information transfer per received photon, approaching fundamental physical limits through the use of advanced modulation formats, photon-counting detection, and optimized decoding techniques.The specific objectives include: 1. Designing and analyzing novel modulation and encoding schemes that increase photon information efficiency, particularly in low-power and photon-starved communication regimes. 2. Evaluating the performance of proposed transmission strategies by comparing achievable information rates against theoretical quantum limits under varying spectral-efficiency conditions. 3. Developing robust decoding and signal-processing methods capable of reliably recovering information from extremely low photon counts in the presence of noise and detection imperfections. 4. Validating theoretical models and system designs through experimental investigations using state-of-the-art single-photon detection facilities. 5. Assessing the practical implications of photon-efficient communication by formulating design principles for future space and long-distance optical communication systems operating near quantum-limited performance.
Methods and techniques that will be developed and used to carry out the research	The research methodology will include: 1. A comprehensive literature review on photon information efficiency, quantum limits of optical communication, modulation formats, and photon counting detection techniques. 2. Development and implementation of robust clock recovery algorithms to enable accurate timing synchronization between transmitter and receiver, particularly under low photon rate and high noise conditions. 3. Theoretical analysis and design of advanced

	modulation formats and decoding strategies aimed at maximizing information per photon, including comparison with fundamental quantum capacity limits. 4. Experimental validation of proposed modulation and decoding techniques using single photon detectors, with performance evaluation accounting for practical detector impairments such as noise, efficiency, and stability.
Educational objectives	1. Develop advanced knowledge in optical and photon efficient communication systems, with a strong focus on modulation formats, synchronization, and information theory. 2. Gain solid theoretical skills in modeling and analyzing communication systems operating near fundamental quantum limits. 3. Acquire hands on experience with state-of-the-art experimental techniques for optical communication, including single photon detection, high speed transmitters, and precise timing systems. 4. Strengthen analytical and problem-solving abilities by bridging theoretical models with experimental validation in realistic laboratory environments. 5. Enhance research and scientific communication skills through the dissemination of results in international journals, conferences, and collaborative research meetings. 6. Develop team working skills through close collaboration with international research groups at Politecnico di Milano and Bell Laboratories, and foster capabilities for lifelong learning and professional development.
Job opportunities	For the ambitious and disruptive objectives of the research, as well as for the reputation of the involved research groups, it is expected that after completion of the PhD program the candidate will be ready for being part of any research team in public and private institutions and centers, universities, and industry.
Composition of the research group	0 Full Professors 4 Associated Professors

	1 Assistant Professors 8 PhD Students
Name of the research directors	Prof. Maurizio Magarini

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Additional support - Financial aid per PhD student per year (gross amount)	
Housing - Foreign Students	--
Housing - Out-of-town residents	--

Scholarship Increase for a period abroad	
Amount monthly	900.0 €
By number of months	6

Additional information: educational activity, teaching assistantship, computer availability, desk availability, any other information

EDUCATIONAL ACTIVITIES (purchase of study books and material, including computers, funding for participation in courses, summer schools, workshops and conferences): financial aid per PhD student.

TEACHING ASSISTANTSHIP: availability of funding in recognition of supporting teaching activities by the PhD student.
There are various forms of financial aid for activities of support to the teaching practice.
The PhD student is encouraged to take part in these activities, within the limits allowed by the regulations.

COMPUTER AVAILABILITY:
1st year: Yes
2nd year: Yes
3rd year: Yes