Engineering Tripos Part IIB, 4B23: Optical Fibre Communication, 2017-18

Module Leader

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Lecturer

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Timing and Structure

Lent term. 75% exam / 25% coursework

Prerequisites

Photonic technology (3B6) and Data transmission (3F4) useful

Aims

The aims of the course are to:

- Provide an overview of the key technologies that underpin modern optical fibre communication systems including the appropriate theory and practice
- Provide a system level perspective to allow progression from devices and subsystems through to systems and networks

Objectives

As specific objectives, by the end of the course students should be able to:

- Explain the salient features of a modern optical fibre communication system employing digital coherent transceivers
- Understand the limitations imposed by both noise and nonlinear properties of the optical fibre
- Be able to analyse performance metrics such as bit error rate for an optical fibre communication link
- Understand the principles of coherent detection as opposed to direct detection receivers
- Understand the role of digital signal processing and forward error correction in modern communication systems
- Be able to design an optical fibre communication link given appropriate constraints

Content

Optical fibre communication systems underpin modern communication systems, from the high capacity submarine cables that link continents to the interconnected mobile basestations used in wireless communications. The module will give an introduction to the theory and practice of modern optical fibre communication systems which achieve a capacity in excess of 100 Gbit/s per wavelength. A systems approach is taken, focusing on the fundamental mathematical modelling of devices, subsystems and systems, to allow students to design and analyse future systems rather than merely reflecting latest technological developments.

Preliminary syllabus

1. **Introduction:** Salient features of multi-wavelength optical fibre communication systems, including a historic perspective and an overview of current systems. Discussion of the difference between modern optical fibre communication systems and legacy systems, in particular transition to digital coherent transceivers, removal of optical dispersion compensation, use of forward error correction and the minimisation of the water absorption peak in modern optical fibres.
2. **An optical fibre as a dielectric waveguide** – Starting from Maxwell's equations the modes and characteristics thereof for a cylindrical optical waveguide are analysed.
3. **Waveguide devices** – Coupled mode theory and its application to the analysis of optical couplers (the 50:50 coupler as a key building block). Electro-optic effects (Pockels and Kerr effect) and the application in a multidimensional Mach-Zehnder modulator. Analysis of micro-ring resonators both as modulators and add drop multiplexers. Analysis of Bragg fibre gratings.
4. **Propagation of pulses in a single mode optical fibre.** Dispersion due to a wavelength dependent refractive index, group velocity and chromatic dispersion. Derivation of linear propagation equation based on slowly varying envelope approximation. Solution of governing propagation equation in linear regime with Gaussian pulses. Polarisation mode dispersion in optical fibres.
5. **Nonlinear Schrödinger equation for pulse propagation in an optical fibre.** Derivation of the nonlinear Schrödinger equation (NLSE). Solving the simplified NLSE – solitons in optical fibres. Extending the NLSE to two polarisations. Other nonlinear effects in optical fibres
6. **Optical amplifiers** – basic concept of gain, noise, and gain saturation. Black box model, amplifier noise figure, noise figure of a cascade (Friis' Formula), simplified model of an optical amplifier. Gaussian approximation of quantum noise. Fourier representation of ASE. Minimum noise figure of a linear amplifier (from Heisenberg uncertainty).
7. **Coherent transceiver photonic technology** – Analysis of push-pull Mach-Zehnder modulator for DP-QPSK modulator. Principle of coherent reception – heterodyne, homodyne and intradyne. Analysis of 2x2 coupler based heterodyne receiver with single ended and balanced receiver. Analysis of passive quadrature network for phase diverse receiver. Move towards digital modems – CMOS data converters, "Walden plots", Heisenberg uncertainty limits for ADC performance.
8. **Noise in optical fibre communication systems** – Sources of noise – transmitter (laser RIN & linewidth, electrical phase noise), receiver (thermal, shot & quantisation, electrical phase noise), and optical line (ASE from amplifiers, nonlinear noise interaction). PIN photodiode as a square law detector. PSD of ASE noise terms in a direct detection receiver. Gaussian approximation of ASE beat noise and the issue for estimating optimum threshold for ASE limited IM/DD systems. Swept threshold measurements to estimate BER and characterisation of receiver sensitivity, including linearised relation between power in dBm and BER when plotted on a double log scale.
9. **Digital coherent receivers –** DSP and its application to coherent optical fibre communication systems, highly parallel CMOS implementation -> FIR filtering. Dispersion compensation, MIMO polarization filtering. Challenges of recovering the phase in systems with finite linewidth lasers with CMOS processing. Blind and decision directed carrier recovery algorithms. Overview of timing estimation algorithms.
10. **Performance analysis for a coherent detection links** - ASE limited versus receiver (shot) noise limited. Analytical approaches including nonlinear Gaussian Noise model. BER analysis for coherent detection of long-haul BPSK, QPSK, PDM-QPSK etc.
11. **Information theoretic limits and future research directions** for optical fibre communication: Shannon theory and challenges for defining the capacity of a nonlinear channel. Upper bounds due to power density in optical fibre and quantum limits for optical communication. Introduction to optical networking.
12. **Industry guest lecture** - provided to enable students to understand the industrial context for the topics covered within the module.

Examples papers

Two example papers will be issued with an example class for each example paper.

Coursework

For the coursework there will be a design exercise worth 25%.

Coursework	Format	Due date & marks
[Optical Network Design] The coursework exercise is to design an optical network to link Cambridge University, UCL, Southampton University, Bristol University and Aston University. Students are required to write a report detailing their proposed design and expected performance. Within the report three possible topologies should be compared and any assumptions made within the design should be explicitly stated. The report should be no more than 10 sides of A4 with minimum font size of 11, however detailed calculations regarding design choices such as fibre type, amplifier spacing, launch power etc. may be included in a technical appendix that is not subject to page limits. Learning objectives: • To be able to calculate the throughput of an optical network • To understand impact of topology on network throughput • To understand the design decisions and trade-offs that occur in network design	Individual Report anonymously marked	Wed week 9 [15/60]

Examination Guidelines

Please refer to Form & conduct of the examinations [2].

Last modified: 18/09/2017 07:09

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