2. Digital Optical Systems based on Coherent and Direct Detection

Optical Communication Systems and Networks
BIBLIOGRAPHY

- Fiber-Optic Communications Systems

- Optical Fiber Communications. Principles and Practice
Modulation formats

**Optical carrier:** \( E(t) = A_0 \cos(\omega_0 t - \phi_0) \hat{e} \)

- **Amplitude modulation** \( A_0 \): **ASK**, Amplitude-shift keying
- **Phase modulation** \( \phi_0 \): **PSK**, Phase-shift keying
- **Frequency modulation** \( \omega_0 \): **FSK**, Frequency-shift keying
- **Polarization modulation** \( \hat{e} \): **PoSK**, information coded by polarization state (not allowed in optical systems based on fiber)

- Most commercial systems are based on ASK (These systems are also known as on–off keying, OOK) → **IM/DD** (intensity modulation and Direct Detection)
- First Differential PSK (DPSK) are being deployed recently
Direct Detection

**ELECTRICAL RECEPTION**

- **Antenna**
  - $E(t) = f(t)\cos(\omega t)$

  - Electrical receiver

  - Amplifiers (& filter/s)

  - $i(t) = CE(t) \propto f(t)$

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**OPTICAL RECEPTION**

- **Optical receiver**
  - Lens (Focusing /collimation)

  - $E(t) = f(t)\cos(\omega t)$

  - $i(t) = C|E(t)|^2 = CP(t) \propto f^2(t)$

  - Amplifier (& filter/s)
Photodetectors

**Thermal**

Variation of radiation makes a change of temperature $\Delta T$ (bolometers). They are slow for communication applications.

**Vacuum devices**

As the *photomultiplier tubes*, which have high sensitivity but require high voltages, are expensive, slow and large. They also have difficulty operating at $\lambda > 1 \, \mu m$.

**Semiconductors**

Incident radiation causes variation of carriers, which in turn causes the modification of the conductivity of the material. They have low sensitivity.

**Photoconductors**

Incident radiation causes variation of carriers, which in turn causes the modification of the conductivity of the material. They have low sensitivity.

**fotodiodes**

Best option in Optical Communications
Coherent Systems

ADVANTAGES:

- Coherent detection can provide a potential improvement up to 20 dB in the receiver sensitivity unlike direct-detection-based systems
  - For a given power budget, this would allow to increase the total length of an optical link (or spacing between repeaters/ amplifiers)
  - Higher transmission rates over existing optical links without reducing repeater spacing is achieved

- Efficient use of the available bandwidth
  - Allows to transmit simultaneously several carriers (frequency multiplexing)
  - Channel spacing can be reduced to 1 - 10 GHz.
    - In IM/DD systems, 100 GHz – channel spacing has been proposed. Latest recommendations (G.694.1) include 50, 25 and 12.5 GHz versions

DISADVANTAGES:

- Receivers become more complex
- Sensitivity to the optical carrier’s phase and frequency degradation in reception
Diagram of a Coherent Detection System

- Received optical signal (modulated)
- Beam combiner
- Detector
- Electronic driver
- Local oscillator
- CW
- Electrical bit sequence
Coherent Systems

- The optical carrier carries modulated/coded information (phase and/or frequency)

- **At receiver:** coherent mixing between the incoming signal and optical wave generated by a stable and reduced spectral width local oscillator.

  **Incoming signal:** \( E_s = A_s \exp \left[ - j(\omega_0 t + \phi_s) \right] \)

  **Local oscillator:** \( E_{OL} = A_{LO} \exp \left[ - j(\omega_{LO} t + \phi_{LO}) \right] \)

- Assuming perfect optical mixing, and recalling than optical power is proportional to the square of the electrical field strength, we have:

  \[
P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi_s + \phi_{LO}),
  \]

  \[
P_s = KA_s^2 \quad P_{LO} = KA_{LO}^2 \quad \omega_{IF} = \omega_0 - \omega_{LO}
  \]

  - if \( \omega_{IF} = 0 \), coherent system with homodyne detection
  - if \( \omega_{IF} \neq 0 \), coherent system with heterodyne detection
Coherent Systems. Homodyne detection

- When the local oscillator frequency equals to optical carrier frequency: \( w_{FI} = w_s - w_{OL} = 0 \)
- The photocurrent generated by the optical detector is proportional to the optical power (or optical intensity):

\[
I(t) = \Re(P_s + P_{LO}) + 2\Re\sqrt{P_sP_{LO}} \cos(\phi_s - \phi_{LO})
\]

\[
I(t) = 2\Re\sqrt{P_sP_{LO}} \cos(\phi_s - \phi_{LO})
\]

\( (P_{LO} \gg P_s \Rightarrow P_{LO} + P_s \approx P_{LO} \), where DC can be eliminated) 

Assuming: \( \phi_s = \phi_{LO} \), there is an improvement of SNR:

\[
\left( \frac{I_{\text{Homodyne Detect}}}{I_{\text{Direct Detect}}} \right)^2 = \left( \frac{2\Re\sqrt{P_sP_{LO}}}{\Re P_s} \right)^2 \Rightarrow \frac{4P_{LO}}{P_s} \gg 1
\]

Main disadvantage: Very sensitive to phase variations

- Accurate control of \( \phi_{LO} \) and \( \phi_s \) could be a solution unless both do not fluctuate
- Solution: Phase control so that the difference between \( \phi_{OL} \) and \( \phi_s \) remains constant (by using phase locked-loops)
Coherent Systems. Heterodyne detection

- Typically, the local oscillator frequency is chosen so that intermediate frequency values range from ~0.1 to 5 GHz.

\[
I(t) = \Re(P_s + P_{LO}) + 2\Re\sqrt{P_s P_{LO}} \cos(w_{IF} t + \phi_s - \phi_{LO})
\]

(following the same considerations we made in homodyne detection)

\[
I(t) = 2\Re\sqrt{P_s P_{LO}} \cos(w_{IF} t + \phi_s - \phi_{LO})
\]

- A SNR improvement is obtained with regard to IM/DD systems. However, this improvement (3dB) is lower compared to the one obtained in homodyne detection

**Advantage:** Simpler optical receivers

- Suitable for optical communications systems
- Unable to demodulate directly optical signal to baseband (it is required a previous demodulation from intermediate frequency to baseband in the electrical domain)
Coherent Systems. Heterodyne detection

- Typically, the local oscillator frequency is chosen so that intermediate frequency values range from ~0.1 to 5 GHz.

\[ I(t) = R(P_s + P_{LO}) + 2R\sqrt{P_sP_{LO}} \cos(w_{IF}t + \phi_s - \phi_{LO}) \]

(following the same considerations we made in homodyne detection)

\[ I(t) = 2R\sqrt{P_sP_{LO}} \cos(w_{IF}t + \phi_s - \phi_{LO}) \]

⇒ A SNR improvement is obtained with regard to IM/DD systems. However, this improvement (3dB) is lower compared to the one obtained in homodyne detection

\[ SNR = \frac{\bar{I}^2}{\sigma^2} = \frac{2R^2P_sP_{LO}}{2e(RP_{LO} + I_d)\Delta f + \sigma_T^2} \]

I Photocurrent which depends on the detection process (homodyne or heterodyne)

The homodyne case (\(\phi_{OL} = \phi_s\)) produces an increase of 3dB with regard to the heterodyne case

If the power level \(P_{LO}\) dominates and can be controlled:

\(\sigma_s^2 \gg \sigma_T^2\) and when \(P_{OL} \gg \sigma_T^2/(2eR\Delta f)\). Also if \(I_d \ll RP_{OL}\)

\[ SNR \approx \frac{RP_s}{e\Delta f} = \frac{\eta P_s}{h\nu\Delta f} \]
Coherent Systems. Heterodyne detection

Diagram of a coherent system based on heterodyne detection

- Incoming optical signal (modulated)
- Local Oscillator
- Photodetector
- Beam combiner
- Bandpass filter
- Lowpass filter
- subcarrier recovery (IF)
- Data out