COST-STSM-CA15127-36923

STSM REPORT

IMPROVEMENTS ON OPTICAL WIRELESS COMMUNICATION SYSTEMS TO AVOID TRANSMISSION FAILURES CAUSED BY WEATHER-BASED DISRUPTIONS

STSM title (detailed): Improvements on Optical Wireless Communication Systems (including Hybrid solutions like combinations with RF-Wireless Technologies and Fiber) to avoid transmission failures caused by Weather-based disruptions

STSM Applicant: Mr. Pasha Bekhrad, Graz University of Technology, Graz (AT), bekhrad@tugraz.at

Host: Dr. Mike Wolf, Optical communication, Ilmenau (DE), Mike.wolf@tu-ilmenau.de

Period: 2017-03-10 to 2017-03-18

Working group: WG2 - Weather-based disruptions

1. Purpose of the visit

We assist since few years to a renewed interest to Free space optics (FSO) telecommunications systems in order to face to increasing needs in high-speed telecommunications. Availability and reliability of such systems are subject to weather conditions (fog, snow, haze, rain, scintillations); the effect of fog being a very predominant factor in the light transmission.

One of my purposes of the visit was to establish contacts with colleagues dealing with the same expertise but my main purpose was twofold. One of them is FSO performance analysis under different weather conditions and modulation formats. Second purpose was however to study the synchronization and channel estimation for optical block-transmission system with intensity modulation and direct detection (IM/DD) at the receiver. The timing synchronization of OFDM/Discrete Multitone Transmission (DMT) systems is often based on auto-correlation algorithms. However, these algorithms do not provide a sharp correlation peak. I tried to study a novel timing synchronization and channel estimation concept for optical block transmission system with IM/DD.

2. Description of the work carried out during the STSM;

During my stay in Ilmenau and work at Communication Research Laboratory, we have analyzed the performance of FSO under different weather conditions and investigated PAM-block transmission with linear Frequency Domain Equalization (FDE) from a theoretical and simulation point of view.

- Performance for channels with a Gaussian low-pass-filters characteristic like a Polymer optical fiber (POF)
- Packet/block synchronization
- Additional non-linear equalization (FDE)

2.1 Introduction to Free Space Optics

Free Space optics is a communication system where free space acts as medium between transceivers and they should be in LOS for successful transmission of optical signal. Medium can be air, outer space, or vacuum. This system can be used for communication purpose in hours and in lesser economy. There are many advantages of FSO like compact size, large bandwidth, lower cost and lease for implementation and no spectrum license. The transmission in FSO is dependent on the medium because the presence of foreign elements like rain, fog, and haze, physical obstruction, scattering, and atmospheric turbulence and attenuation are some of these factors. Different studies on weather conditions and techniques for a 10 Gbps FSO system employed to mitigate their effect, are discussed in this report.

In the following Figure, the basic design of Free Space Optic link is illustrated.

Pseudo-Random bit sequence (PRBS) generator, generates information signal in the form of binary pulses, NRZ pulse generator, The binary pulses in the form of an electrical signal are directed toward NRZ pulse generator which converts these binary pulses to electrical signals, Mach-Zender modulator (MZM), converts the electrical signal to an optical signal and a continuous wave laser which is the input of MZM, have been used in transmitter part whereas the receiver section consists of an APD photodiode, converts this optical signal to its corresponding electrical signal and a low-pas Bessel filter, removes any high-frequency noise present in the signal. Furthermore, to analyze the performance of the communication link BER analyzer has been used. The simulation parameters used, shows in table 1.

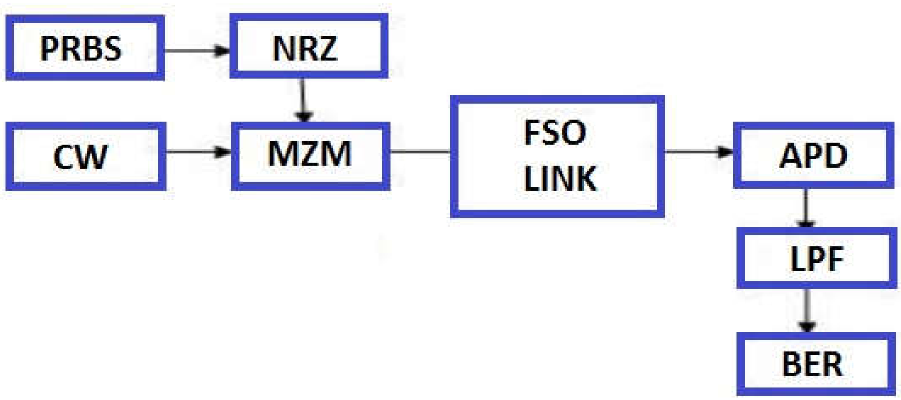


Figure 1. Free Space Optics Link

Table 1. Simulation Parameters

Parameter		Description/ Value
Transmitting wavelength		1550 nm
Transmitting power		4- 8 dB
Antenna diameter		30 cm
Link distance		2000 m
APD multiplication factor		1
Data rate		10 Gbps
APD quantum efficiency		0.8
Filter type		Bessel Filter
APD dark current		1
Attenuation of the free space medium between the transmitter and the receiver	For Clear weather	0-3 dB/Km
	For haze	5 dB/Km
	For fog	22 dB/Km

2.1.1 Different Weather Effects

Performance of FSO is affected by different weather conditions. There are different weather effects like, rain, snow, turbulence and etc. Each of these conditions are explained below.

- Fog, Haze, Mist, Smoke and Smug: Increased droplet concentration, reducing visibility range. Decrease in temperature. From 0.22 – 272 dB/km of loss.
- Rain: Heavy rainfall (150 mm/hour) cause more than 20 - 30 dB/km of loss.
- Snow: Attenuations are related to: amount of LWC (dry and wet snow), snow flake size and snowfall rate. Light snow ~3 dB/km power loss.

- Clouds: Clouds are formed: As air rises it cools due to topography, convergence, convection and fronts, surface cools off quickly by emitting radiation, Air moves over colder surface/into cooler area. Optical attenuations can well exceed 50 dB/km and more and result in complete link blockage.
- Turbulence: Random changes in refractive index due to temperature variations.
- Results in increased BER but not complete link outage. Fades can well increase
- dB depending upon link range and the propagation path.
- Clear air absorption: Caused mainly due to: Molecular absorption (mainly by H2O, CO2, O2 and O3 gases) Aerosol absorption (dust, smoke, water drops). Absorption increases with increased humidity.
- Dust and sand storms: Likely only in desert areas.

2.1.2 Summary of different possible solutions to tackle above limitations

- Fog, Haze, Mist, Smoke and Smug: Transmit power control, Using longer wavelengths, Hybrid FSO/RF, Diversity, Use of more efficient modulation techniques, Adaptive optics, Rate adaptive modulation, Planning and site measurements.
- Rain: Hybrid FSO/RF, Changes in FSO link designs based on seasonal and
- diurnal variations of rain.
- Snow: Transmit power control, Hybrid FSO/RF, Changes in FSO link designs based on seasonal and diurnal variations of snow, Choosing appropriate wavelengths for transmission.
- Clouds: Hybrid FSO/RF, Longer optical wavelengths, Adaptive optics, Site diversity, High altitude platforms.
- Turbulence: Coding, e.g. LDPC, FEC MIMO, Diversity reception (Temporal and Spatial), Adaptive Optics, Robust modulation techniques, Coherent detection not used due to Phase, Multi-beam systems, Collection optics larger than scintillation structure.
- Clear air absorption: Selection of proper wavelength windows for transmission.
- The main advantages of FSO links compared to microwave links are small high gain antennas, light terminals, highest possible data rates at low signal power, no interference with other transmission systems and tap-proof operation using coherent methods.

Increasing the reliability and availability of optical wireless links is achievable on the one hand with special coding techniques, auto-tracking methods and automatic gain control and on the other hand with combined hybrid networks (FSO and microwave systems). Microwave and FSO links have similar properties regarding offered data rates and flexibility of setup, but operate under different conditions, with their benefits and challenges. The benefit of a combination of communication systems operating at millimeter waves and optical waves is the complementary behavior of each technology during different weather conditions.

Employing a hybrid network consisting of an FSO link and a backup link in the GHz frequency range offers high availability besides providing comparable data rates. Rain is the dominant cause for temporary variable attenuation in the microwave link, whereas fog is the most important cause for attenuation in the optical wave link.

Research studies have shown that optical attenuations can reach up to 120 dB/km in moderate continental fog environments in winter season and 480 dB/km in dense fog environments in summer months. Besides different fog conditions; rain and snow restrict FSO availability. The solution lies in the use of a backup link as a supplement to the prime FSO link to ensure a sufficiently high overall link availability and reliability. The availability of a hybrid system comprising of an FSO main link and 40 GHz back up link was measured higher percentage compared to availability of FSO alone. The idea behind using such a hybrid network is to utilize the potential of the backup link when main link is not fully functional.

The main challenge to implement an outdoor short-range optical wireless link is the atmospheric attenuation, caused by the absorption and scattering. Water particles and carbon dioxide mainly cause the absorption of optical signals, whereas fog, rain, snow and clouds cause the scattering of optical signals transmitted in free space.

a) Fog/Cloud Attenuation effect on FSO/GHz links

Among various atmospheric effects on FSO communication, fog is the most deterrent attenuating factor. For a stand-alone FSO system, fog can cause attenuations of 100 dB/km, while rain at a thunderstorm at a rain rate of 150 mm/h only can generate attenuations of 25 dB/km. Optical attenuations within clouds and fog are assumed to behave similarly as has been observed by various authors in the literature. Fog causes significant attenuation of the optical signals for considerable amount of time and is thus highly deterrent for achieving high availability in FSO transmissions. The main reason of significantly high attenuations due to Mie scattering in different fog conditions is that the size of fog particles is comparable to the transmission wavelengths of optical and near infrared waves. To predict fog attenuations based on visibility range estimate, three models are widely used and they are the Kruse, Kim and Al-Naboulsi models. Compared to effect of fog on FSO link, effect of fog on GHz links for small fog droplets also cause scattering and significant attenuation for backup radio frequencies greater than 10 GHz. While the effect on frequencies lesser than 10 GHz is ignorable. In case of fog droplets with size lesser than 0.01 cm and frequencies below 200 GHz.

A combination of FSO and 40 GHz RF links exhibit promising results under fog. In general, selecting a suitable frequency for the backup link of a hybrid network dependent upon the probability of occurrence of a certain weather effect at a particular location.

b) Rain Attenuation for FSO/GHz links

Fog and rain droplets randomly attenuate the optical signal passes through the earth atmosphere. The main attenuation factor as I mentioned for optical wireless link is fog but rain also imposes certain attenuations for such links. As size of rain droplets becomes large enough to cause reflection and refraction process, these droplets cause wavelength independent scattering. Although the propagation of microwave signals is greatly disturbed by fog, clouds and dust particles but rain is the major attenuating factor at frequencies above 10 GHz. In the Microwave link a rain rate of 150 mm/h can cause up to 50 dB/km attenuation (up to 35 dB/km for 40 GHz) while fog does not particularly matter, and increased humidity causes less than 5 dB/km. To achieve high availability, a high link margin is necessary for each single technology and Bad weather conditions are limiting Free Space Optics applications mainly within the last mile access area and are requiring high output power for a longer range microwave system.

2.1.3 Result

The performance of a Free Space Optical Communication Link is analyzed using different modulation formats and weather conditions. The performance of the FSO link is analyzed on the basis of Q Factor, total received power, and SNR of the received signal.

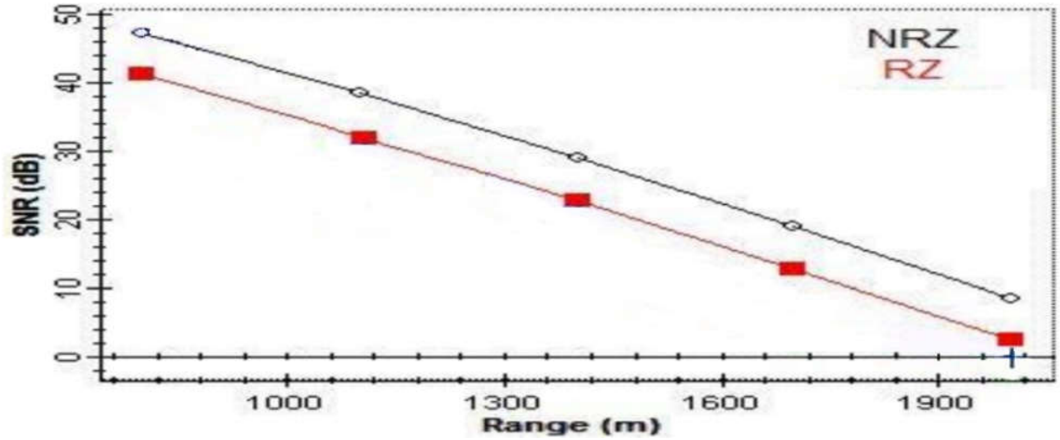


Figure 2. SNR vs. Range for NRZ and RZ formats

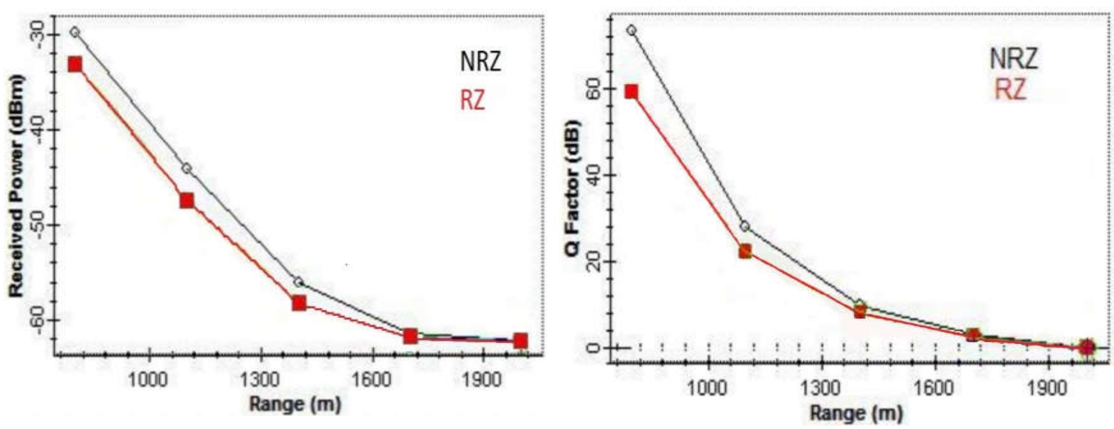


Figure 3. Received power/Q factor vs. Range for NRZ and RZ formats

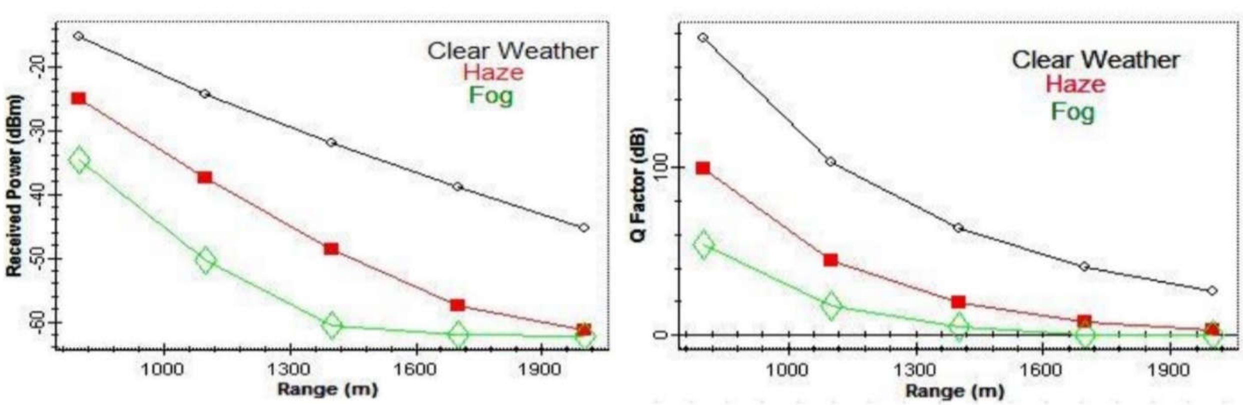


Figure 4. Received power/Q factor vs. Range for Different weather conditions

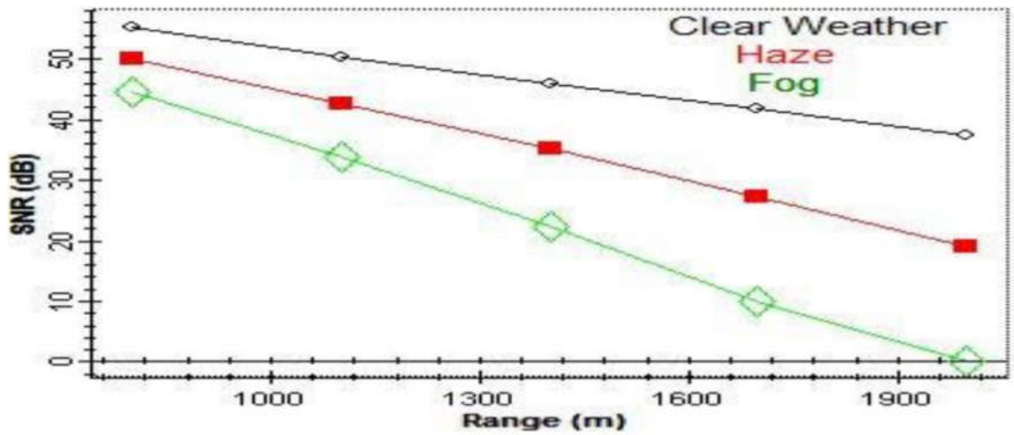
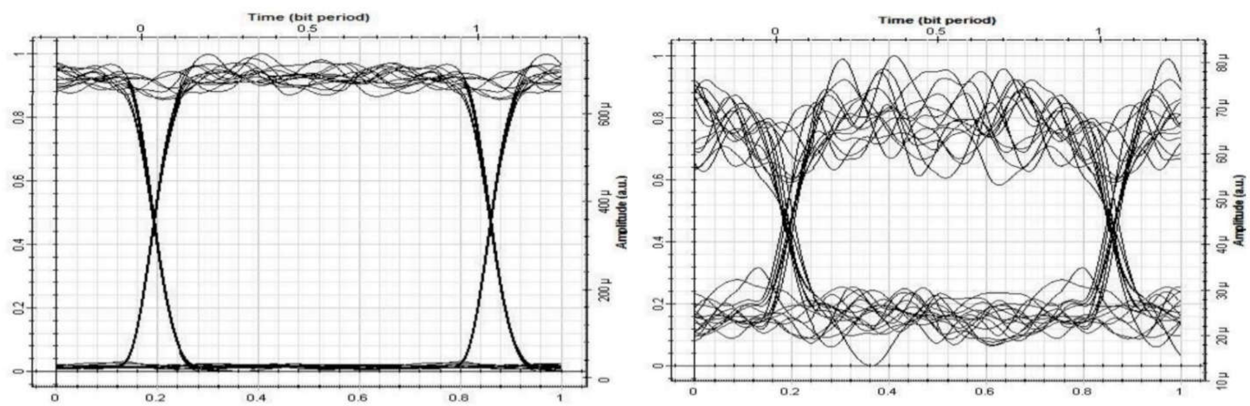


Figure 5. SNR vs. Range for Different weather conditions



(a) **(b)**

Figure 6. Received signal under Clear weather (a) and Haze weather (b)

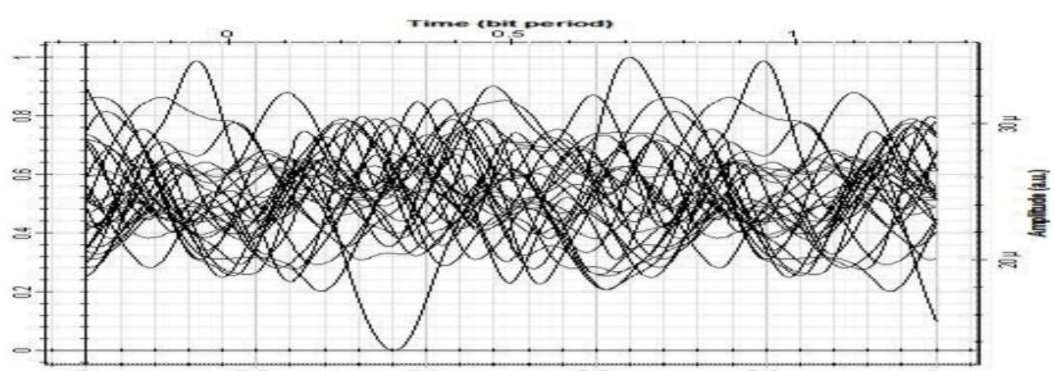


Figure 7. Received signal under Fog conditions

From the results, it can be seen that as we move from clear weather conditions to heavy fog weather conditions, Q factor of the received signal and maximum transmission distance both decreases. Also, NRZ modulation format performs better as compared to RZ modulation format in an FSO communication link.

2.2 Introduction to Synchronization and Channel estimation

The concept is based on Golay complementary sequence. As these sequence are binary, multiplier-less matched filters can be implemented in order to use the cross-correlation function for the timing synchronization. Golay complementary sequence enable an estimation of the channel impulse response directly in the time domain since they have ideal correlation properties.

Why PAM-block transmission, why not OFDM/DMT?

A)

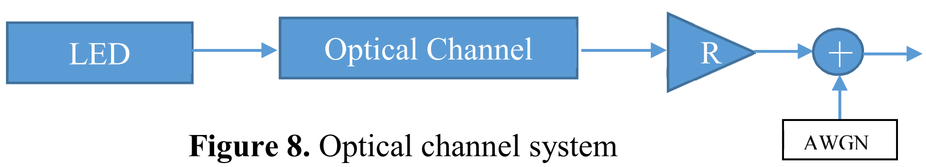


Figure 8. Optical channel system

- For IM/DD, all signals are real valued and non-negative.
- quadrature up-conversion to a pair of sinusoidal optical carriers is impossible
- bandwidth efficiency of DC-biased OFDM suffers by a factor 2 compared to field modulation
- even if LED non-linearities are not considered, DC-biased OFDM with optimal bit loading will not outperform PAM
- PAM (based on rectangular pulses) does not suffer from LED non-linearities

B)

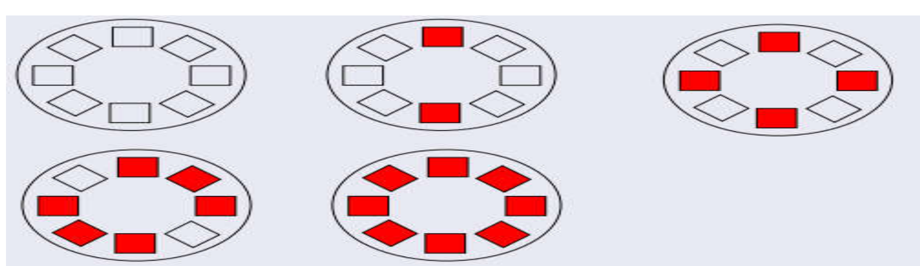


Figure 9. 5 level PAM example

5-PAM can be combined with a ‘8B4P’ line code to ensure DC balance.

2.3 Block Sync in RF

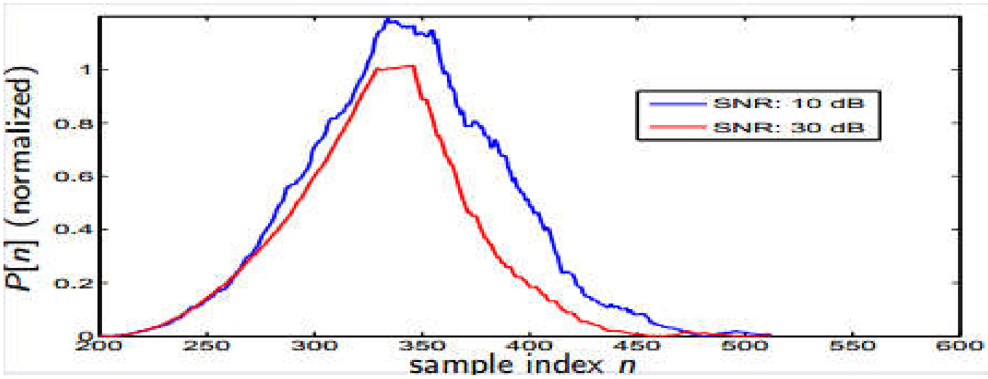


Figure 10. Schmidl-Cox Approach

- Auto-correlation removes effect of carrier frequency offset ⇒not required for IM/DD.
- Worse noise performance: noise becomes chi-square distributed.
- Very un-precise timing due to worse edge steepness.
- Not suitable for direct channel impulse response measurement.

2.4 Block Sync for IM/DD

Use cross-correlation/matched filter based detection.

- Use binary sequences

  - corresponding matched FIR filters are multiplier-less
  - lowest peak to average power ratio
  - matches to the lowest PAM modulation order
  ⇒ highest energy efficiency

- Best noise performance

- Exploit correlation properties
  - m-sequences are good, but
  - Golay complementary sequences (CS) provide ideal correlation properties

- How to obtain a bipolar Rx-signal?
  - the built-in Rx high-pass-filter maps a unipolar signal into a bipolar

2.5 Channel Estimation for IM/DD

Once time sync is obtained, we have a direct estimate of the impulse response.

3. Description of the main results obtained;

- The impact of two modulation formats and weather conditions on the performance of Free Space Optical Communication system has been analyzed and discussed. Performance has been analyzed on the basis of Q Factor, SNR, and total power of the received signal. From the results, it can be observed that Q Factor lies in the range 77 to 12 dB and total received power lies in the range -30 to – 54 dBm and SNR lies in the range 48 to 30 dB for NRZ modulation format and link distance of 1.5 Km. From the results presented and discussed, it can be concluded that NRZ modulation format performs better as compared to RZ modulation format in an FSO communication link.

- Hybrid network, a combination of FSO main link and radio frequency back up link, is a lasting solution to overcome the atmospheric attenuations

- I have studied IM/DD that does not suffer from a carrier frequency offset (as RF). Therefore, no auto-correlation detection (Schmidl/Cox) required
- Cross-correlation / matched filter based detection is inherently multiplier-less, if binary signals are used.
- The Golay complementary sequence are ideal candidates for the synchronization and channel estimation of optical block transmission system with intensity modulation and direct detection. Therefore, ideal correlation properties, precise time synchronization and direct estimation of the impulse response (noise reduction)
- The high-pass characteristic of the receiver maps a unipolar into a bipolar signal
- For rectangular transmit pulses of duration T, the ADC clock period needs to be T /2 or lower
- For N_{CS} = 256 and fractional equalization, the power penalty due to the proposed time- and channel-estimation is $\leq$ 0.5 dB

4. Future collaboration with the Host institution (if applicable);

I think we managed to start very good relations with the colleagues from TU Ilmenau. Because we work at the same field and we will support each other. We can investigate the physical layer for our future collaboration

- Modulation/coding
- Equalization
- Synchronization

And also establishing FSO installation with roughly more than 50 optical links to create a solid case study as well as create the geographically correlated measurement database of atmospherically effects on the FSO technology in all environments.

5. Foreseen publications/articles resulting from the STSM (if applicable);

The two following titles would lead to joint publications.

- Proof of principle with a truth channel (Polymer optical fiber (POF), multimode- fibers, VLC)
- Investigation of a clock-tracking algorithm

I would like to thank all colleagues at TU Ilmenau, specially to Dr. Mike Wolf, who was very supportive and helpful for my entire stay.