OPTICAL RECEIVER BANDWIDTH ENHANCEMENT USING BOOTSTRAP TRANSIMPEDANCE AMPLIFICATION TECHNIQUE

SITI SARA BINTI RAIS

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Faculty of Electrical Engineering
Universiti Teknologi Malaysia

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To my beloved mother and father

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ABSTRACT

Optical wireless link operates in high noise environments owing to ambient conditions such as sun for outdoors and fluorescent for indoors. The performance of free-space optics is subjected to several atmospheric factors like environmental temperature, fog, smoke, haze and rain. Signal-to-noise ratio (SNR) can vary significantly with the distance and ambient noise. Limited range due to ambient noise is the dominant noise. A good sensitivity and a broad bandwidth will invariably use a small area photodiode where the aperture is small. However, free-space optics requires a large aperture and thus, the receiver is required to have a large collection area, which may be achieved by using a large area photodetector and large filter. However, large area of photodetector produces a high input capacitance that will be reduced the bandwidth. Typical large photodetection area commercial detectors has capacitance are around 100-300pF compared to 50pF in fiber link. Hence, techniques to reduce the effective detector capacitance are required in order to achieve a low noise and wide bandwidth design. In this project, modeling and analysis the bootstrap transimpedance amplifier (BTA) of front-end receiver for input capacitance reduction has been simulated. This technique improved the conventional transimpedance amplifier (TIA) bandwidth up to 1000 times with an effective capacitance reduction technique for optical wireless detector.

ABSTRAK

Rangkaian optik tanpa wayar beroperasi dalam keadaaan hingar yang tinggi disebabkan oleh persekitaran seperti cahaya matahari untuk aktiviti luar manakala aktiviti dalaman terdedah kepada cahaya fluorescent. Prestasi komunikasi optikal tanpa wayar bergantung kepada faktor-faktor persekitaran seperti suhu, kabus, asap dan hujan. Nisbah isyarat kepada hingar boleh berubah bergantung kepada jarak dan persekitaran hingar. Hingar ini merupakan hingar yang paling dominan. Disebabkan persekitaran tanpa wayar, hingar dan kehilangan isyarat laluan sangat tinggi. Penggunaan kawasan kecil fotodiod dapat mengekalkan kepekaan dan keluasan lebar jalur yang baik di mana bukaan fotodiod adalah kecil. Tetapi dalam ruang bebas optik memerlukan bukaan fotodiod yang besar di mana ia memerlukan kawasan pengumpulan yang besar dan ini boleh dicapai menggunakan fotodiod yang mempunyai keluasan yang besar. Bagaimanapun, penggunaan fotodiod ini akan menyumbang kepada peningkatan input kemuatan sekaligus menyebabkan lebar jalur berkurangan. Kebiasaan nilai kemuatan fotodiod yang besar di pasaran adalah dalam lingkungan 100-300pF berbanding 50pF yang digunakan dalam rangkaian fiber optik. Oleh yang demikian, teknik untuk mengurangkan kesan kemuatan fotodiod diperlukan untuk mencapai hingar yang rendah dan dalam masa yang sama juga, memperolehi lebar jalur yang tinggi. Dalam projek ini, BTA yang dimodelkan dan dianalisis untuk mengenalpasti kesan kemuatan telah pun disimulasi menggunakan perisisan Matlab. Teknik ini memperbaiki lebar jalur TIA yang konvensional lebih 1000 kali ganda dengan mengurangkan kesan kemuatan dan sangat sesuai digunakan bagi rangkaian optic tanpa wayar.

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C_f - feedback capacitance

R_f - feedback resistance

R_L - equivalent shunt resistance

C_d - photodiode capacitance

C_{in} - total capacitance to the front-end receiver

R_e - emitter resistance

C_s - amplifier input capacitance

A_0 - DC gain amplifier

i_d, i_{PD} - current source of photodetector

f - cut-off frequency

E - electric field intensity

w_a - dominant pole frequency

w_0 - unity gain frequency

DC - direct current

AC - alternating current

Hz - Hertz

V_0 - output voltage

V_s - source voltage

K - Boltzman’s constant

T - absolute temperature

B,BW - bandwidth

msec - milliseconds

nsec - nanoseconds

A - area of the depletion region

l_d - depletion region length

LIST OF ABBREVIATIONS

TIA	-	Transimpedance Amplifier
BTA	-	Bootstrap Transimpedance Amplifier
Clk	-	clock
PD	-	photodetector
AGC	-	automatic gain control amplifier
LA	-	limiting amplifier
MAs	-	main amplifiers
CDR	-	clock and data recovery
MUX	-	multiplexer
DMUX	-	demultiplexer
LD	-	laser diode
CMU	-	clock multiplication unit
FSO	-	free space optic
Op-amp	-	operational amplifier
PCB	-	printed circuit board
APD	-	Avalanche Photodiode
CR	-	multiplication of capacitance and resistance
FET	-	Field Effect Transistor
RF	-	Radio frequency
WDM	-	wavelength division multiplexing
FOV	-	field of view
OW	-	optical wireless
MSD	-	multi-spot diffusing
SNR	-	signal-to-noise ratio

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CHAPTER 1

INTRODUCTION

A generalized optical communication link is well illustrated in Figure 1.1 [5]. The information to be transmitted to the receiver is assumed to exist initially in an electrical form. The information source modulates the field generated by the optical source. The modulated optical field then propagates through a transmission channel such as an optical fiber or a free-space path before arriving at the receiver.

The receiver may perform optical processing on the incoming signal. The optical processing may correspond to a simple optical filter or it may involve interferometers, the introduction of additional optical fields, or the use of an optical amplifier. Once the received field is optically processed it is detected. The photodetection process generates an electrical signal that varies in response to the modulations present in the received optical field. Electrical signal processing is then used to finish recovering the information that is being transmitted.

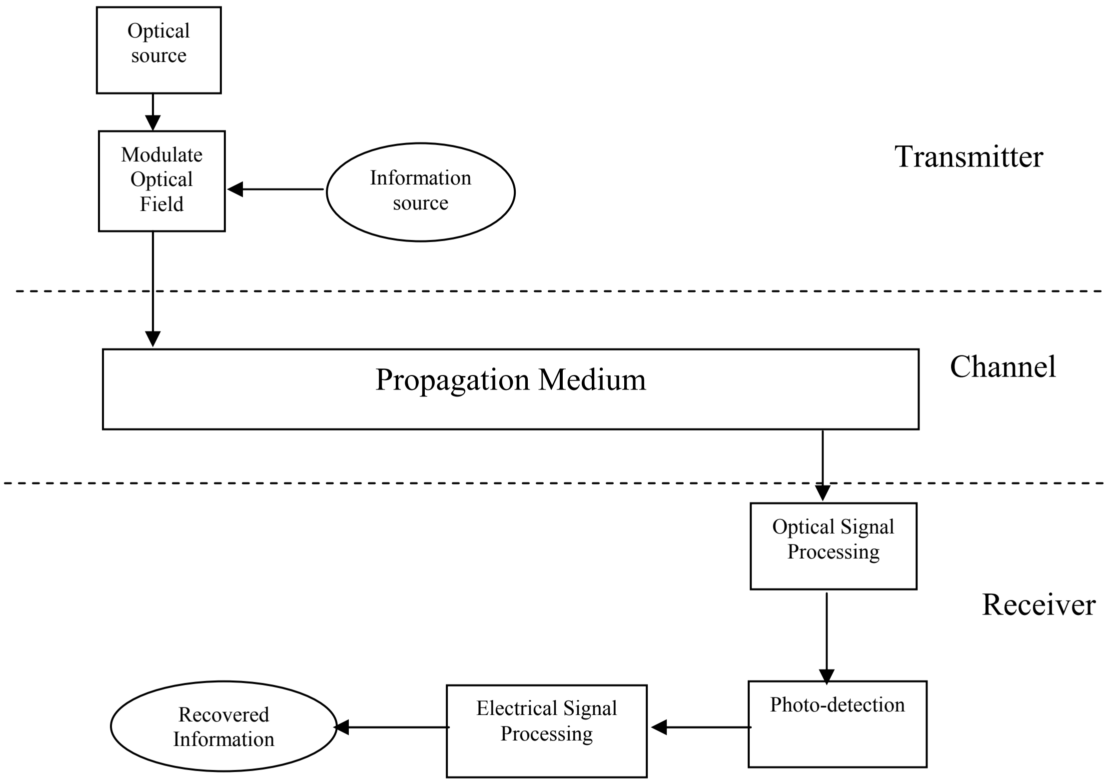

Figure 1.1 A generalized optical communication link [5]

1.1 Fiber-Optic Systems

The block diagram of a typical optical receiver and transmitter for optical fiber link is shown in Figure 1.2 [15]. The optical signal from the fiber is received by a photodetector (PD), which produces a small output current proportional to the optical signal. This current is amplified and converted to a voltage by a transimpedance amplifier (TIA). The voltage signal is amplified further by either a limiting amplifier (LA) or an automatic gain control amplifier (AGC Amplifier). The LA and AGC amplifier are collectively known as main amplifiers (MAs) or post amplifiers.

The resulting signal, which is now several 100 mV strong, is fed into a clock and data recovery circuits (CDR), which extracts the clock signal and retimes the data signal [15]. In high-speed receivers, a demultiplexer (DMUX) converts the fast serial data streams into n parallel lower-speed data streams that can be processed conveniently by the digital logic block. Some CDR designs (those with a parallel sampling architecture) perform the DMUX task as part of their functionality, and an explicit DMUX is not needed in this case [15].

The digital logic block descrambles or decodes the bits, perform error checks, extracts the payload data from the framing information, synchronizes to another clock domain, and so forth. The receiver just described also is known as a 3R receiver because it performs signal re-amplification in the TIA (and the AGC amplifier, if present), signal re-shaping in the LA or CDR, and a signal re-timing in the CDR [15].

On the transmitter side, the same process happens in reverse order. The parallel data from the digital logic block are merged into a single high-speed data stream using a multiplexer (MUX). To control the select lines of the MUX, a bit-rate (or half-rate) clock must be synthesized from the slower word cock. This task is performed by a clock multiplication unit (CMU). Finally, a laser driver or modulator driver drives the corresponding optoelectronics device. The laser driver modulates the current of a laser diode (LD), whereas the modulator driver modulates the voltage across a modulator, which in turn modulates the light intensity from a continuous wave (CW) laser. Some laser/modulator drivers also perform data retiming, and thus require a bit-rate (or half-rate) clock from the CMU (dashed line and red colour in Figure 1.2).

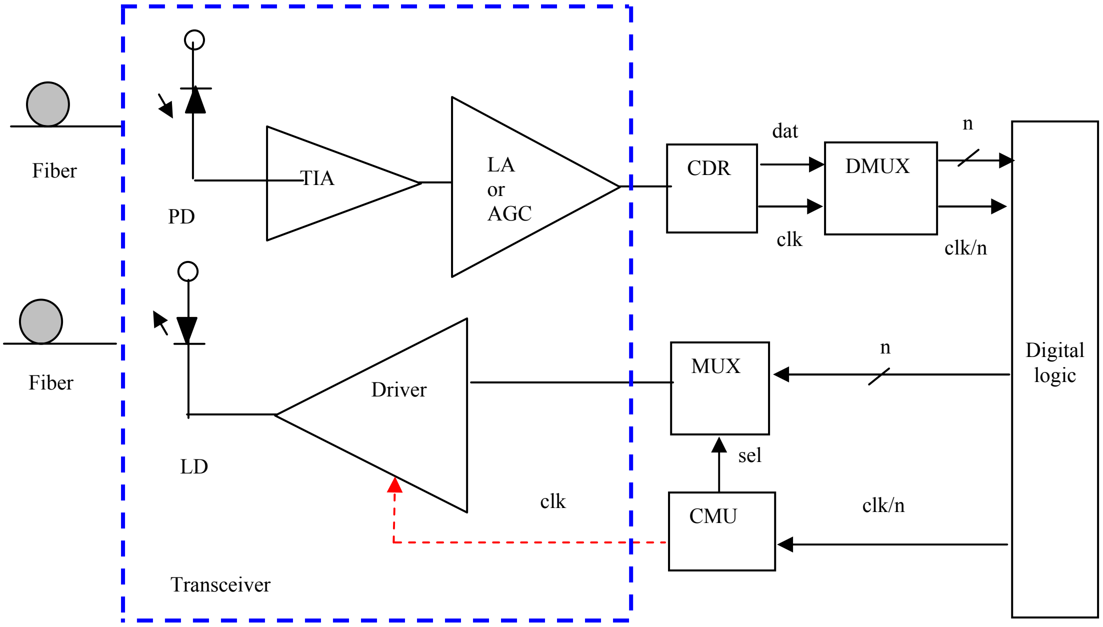

Figure 1.2 Block diagram of an optical receiver (top) and transmitter (bottom)[15]

1.2 Free-Space Systems

The high data-rate capability of optical communication systems also make them particularly attractive for use in free-space systems. As the amount of data available continues to grow, there will be increasing need to efficiently distribute the information for further processing, analysis and presentation. Rapidly reconfigurable communication, treaty verification, natural resource determination, atmospheric sensing, weather forecasting and environmental monitoring are functions that are often best performed from satellites. Any single satellite could directly transmit data down to the Earth's surface, but the costs and difficulties involved in maintaining a large number of individual ground stations can be prohibitive. A space-based communication network that allowed satellites placed in a variety of orbits such as low-earth-orbit (LEO), high-earth-orbit (HEO) or geosynchronous-earth-orbit (GEO) to communicate with each other would provide increases in flexibility and data availability.

Optical techniques will not replace microwave systems in all applications, however. Low data-rate systems and applications requiring Earth coverage from a single antenna are often better serve by microwaves. The optimum role for optical communications is most likely to be in providing the high data-rate (100+ Mbps) trunk lines [5].

With the high data-rates circulating in the spaceborne network, the problem of transmitting the information back to earth arises. Optical communication can also provide connectivity between satellites and Earth if ground station site diversity is employed. It is desirable to place the various ground sites far enough apart to guarantee that they are located in uncorrelated weather systems and that there is a high probability that at least one of the sites will have a clear, unobstructed view to the satellite. The ground sites would then be interconnected via conventional high data-rate optical fiber technology.

The major subsystems of a free-space optical communication link are illustrated in Figure 1.3 [5]. The telescopes, spatial acquisition, spatial tracking and point-ahead subsystems are used to establish and maintain a stable line-of-sight between the platforms that wish to communicate.

Telescopes are frequently mounted in gimbals so that they can point to a variety of locations such as cross-orbit, down at the Earth, or up towards a relay satellite. The spatial tracking system utilizes the telescope’s gimbals to accomplish coarse pointing and uses small, high bandwidth, movable mirrors to accomplish fine tracking.

There are some issues on optical wireless or Free Space Optics (FSO) for instance ambient conditions, range aspects of Bit Error Rate (BER) and Signal to Noise Ratio (SNR), optical spectrum and eye safety considerations. Optical wireless link operates in high noise environments owing to ambient conditions such as sun for outdoors and fluorescent for indoors. There are a limitation of range aspects in FSO such as BER and SNR. The optical wireless link operates with limited power on account of eye safety considerations like IR hotspots. High power optical could hazard to human eye.

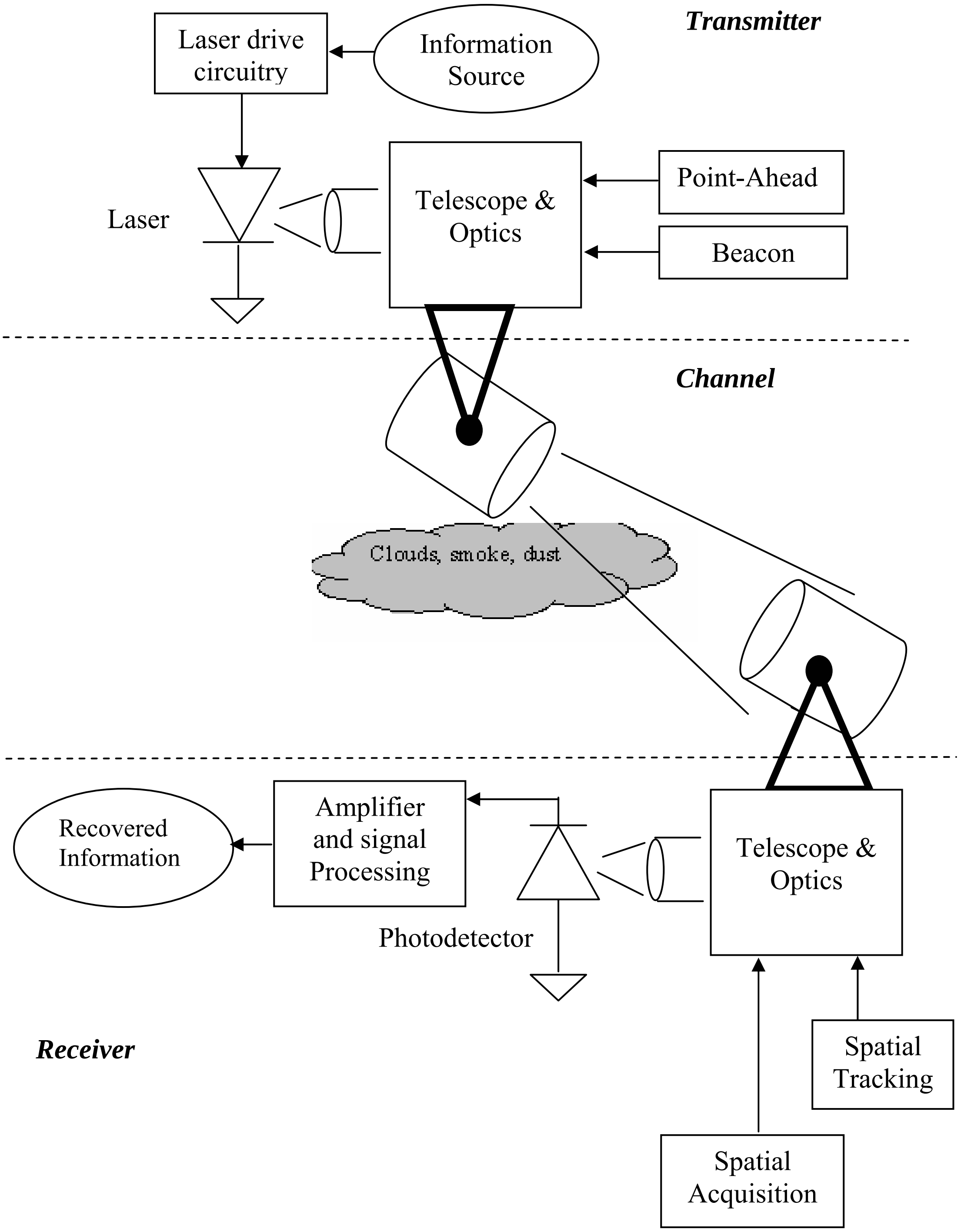

Figure 1.3 Block diagram of a free-space system [5]

1.3 Objectives

Objectives of this project are clarified below.

1.3.1 To improve receiver performance and bandwidth enhancement

The main objective of this project is to improve front-end receiver performance and bandwidth enhancement can perform high gain-bandwidth using bootstrapping technique; so called Bootstrap Transimpedance Amplification (BTA). The BTA should be improved especially in terms of bandwidth enhancement compared to transimpedance technique.

1.3.2 The design will be modeled and simulated using Matlab

The improvement of bandwidth can be modeled and simulated using Matlab. All the comparisons between frequency response of Transimpedance and Bootstrap Amplification can be plotted to analyze the for performance characterization.

1.4 Scopes

A free-space optical system is shown graphically in Figure 1.4. The main scope concentrates on the front-end receiver in a box which contains only a detector and preamplifier.

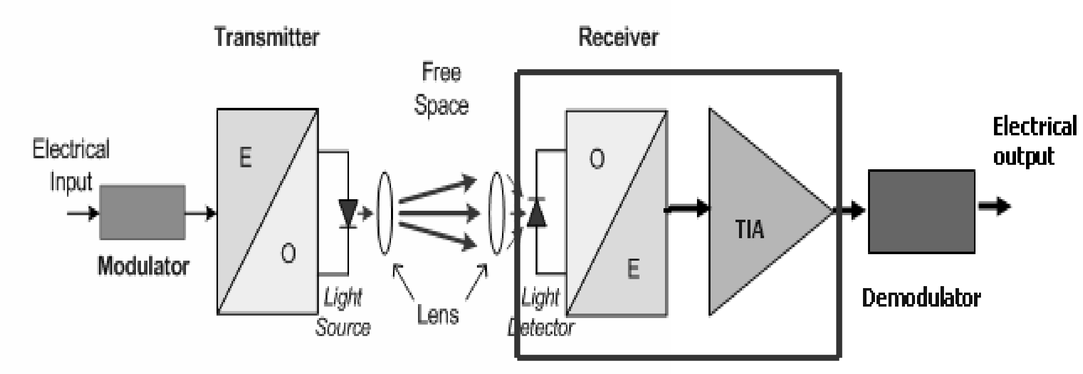

Figure 1.4 Free-Space Optical Systems

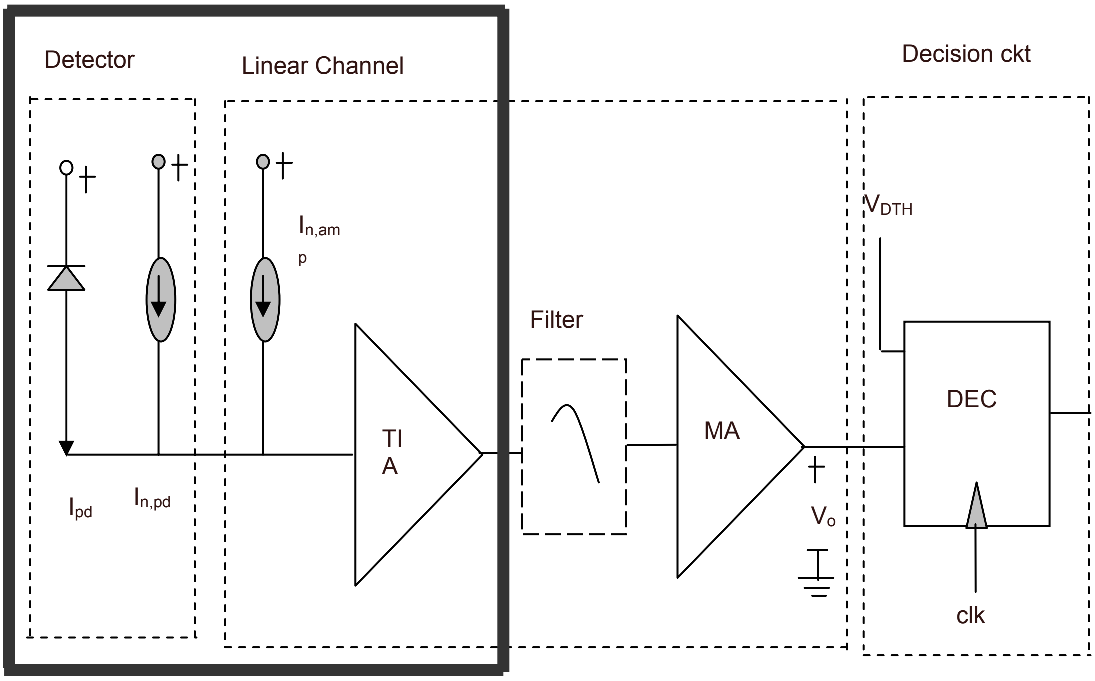

Figure 1.5 Basic Receiver Models [15]

The basic receiver model consists of [15]

i. A photodetector
ii. A linear channel model that comprises the transimpedance amplifier (TIA), the main amplifier (MA) & optionally a Low Past Filter (LPF)
iii. A binary decision circuit with a fixed threshold (VDTH)

As mentioned before, we are only concerned with a detector and TIA as shown in a box in Figure 1.5. The detector we used is a p-i-n photodiode while Bootstrap Transimpedance Amplification technique is used as a preamplifier.

1.4.1 Detector model

A detector's function is to convert the received optical signal into an electrical signal, which is then amplified before further processing. A p-i-n photodetector have been studied as a detector model. In all cases, we have found that the signal current is linearly related to the received optical power and that the noise current spectrum is approximately white & signal dependent [15]. We model the p-i-n photodiode using the simple cylindrical volume structure as illustrated further in Chapter II. We assume the system is ideal where noise analysis is ignored in this detector.

1.4.2 Transimpedance amplifier (TIA)

The TIA can be modeled with a complex transfer function that relates the output voltage V_o to those of the input current I_{PD}. An optical receiver's front-end design configurations can be built using contemporary electronics devices such as operational amplifier (op-amp), bipolar junction transistor (BJT), field effect transistor (FET), or high electron mobility transistor. The receiver performance that is achieved will depend on the devices and design techniques used. In this project, a Bootstrap Transimpedance Amplification (BTA) technique is used to perform high gain-bandwidth.

1.5 Problem Identified and Solution

A fundamental requirement in the design of an optical receiver is the achievement of high sensitivity and broad bandwidth. These two features are, generally, in conflict with a capacitive device, as the CR product, of course, increases with load resistance. In any photodetector application, capacitance is a major factor which limits response time. Decreasing load resistance improves this aspect, but at the expense of sensitivity [2].

There are many techniques have evolved because of the following basic features of photodiode :

a) It essentially acts as a current source

b) It is capacitive

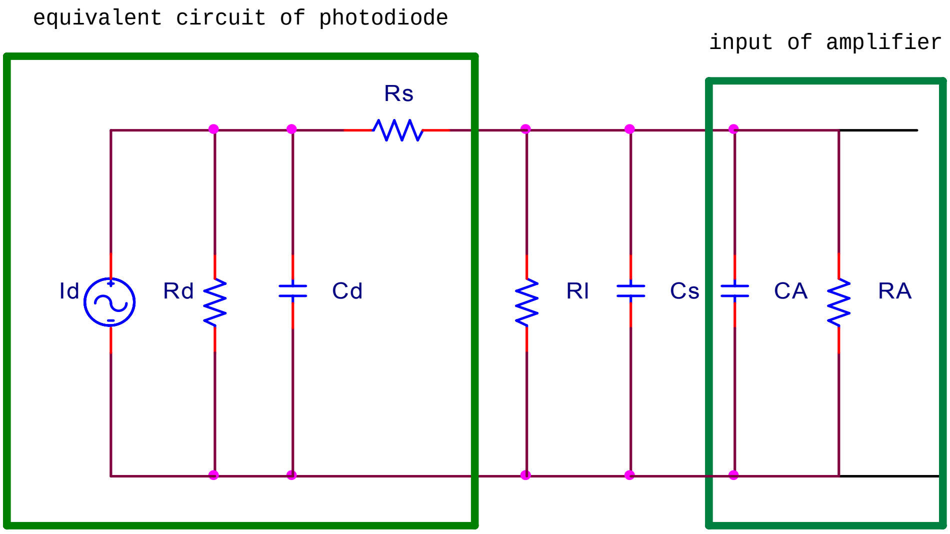

Figure 1.6 Generalized circuits for photoreceiver

Id : photodiode current

Cd : photodiode capacitance

Rs : series photodiode resistance

Rl : load resistance

Rd : internal photodiode resistance

Cs : stray capacitance

CA : amplifier input capacitance

RA : amplifier input resistance

A generalised equivalent circuit is shown in Figure 1.6, from which the upper cut-off frequency is, simply,

$$f = \frac{1}{2\pi R_L C_{in}} \tag{1.1}$$

where C_{in} is a total capacitance and R_L is an equivalent shunt resistance.

Due to the wireless environments, there are high path loss and background noise. A good sensitivity and a broad bandwidth will invariably use a small area photodiode where the aperture is small. But, FSO require a large aperture and thus, the receiver is required to have a large collection area, which may be achieved by using a large area photodetector and large filter. However, large area of photodetector produces a high input capacitance that will be reduced the bandwidth.

The total capacitance to the front-end of an optical receiver, C_{in} is given by [4]

$$C_{in} = C_d + C_s \tag{1.2}$$

where C_d is a photodetector capacitance and C_s is an amplifier input capacitance. We need to minimize in order to preserve the post detection bandwidth. It is necessary to reduce R_L corresponding to the equation (1.1) to increase the bandwidth. Consequently, the thermal noise element due to the load resistor will increase. This relationship is given by [4]

$$i^2_{n(Rl)} = \frac{4KTB}{R_L} \tag{1.3}$$

where K is Boltzmann's constant, T is the absolute temperature and B is the post-detection (electrical) bandwidth of the system.

Thus, the trade-off becomes either to lower R_L to give a high bandwidth, or increase R_L to give low noise currents. Therefore, in this project we introduce BTA to enhance the optical wireless receiver bandwidth by reducing input capacitance, C_{in} employing BTA.

An optical receiver's front-end design can be usually grouped into 1 of 4 basic configurations [5]:

a) A resistor termination with a low-impedance voltage amplifier
b) A high impedance amplifier
c) A transimpedance amplifier
d) A noise-matched or resonant amplifier

Any of the configurations can be built using contemporary electronics devices such as operational amplifiers (Op-Amp), bipolar junction transistors (BJT), field effect transistors (FET) or high electron mobility transistor (such as CMOS). The receiver performance that is achieved will depend on the devices and design techniques used. The theory of the Bootstrap Transimpedance Amplifier (BTA) was found but very less effort on the modeling. Therefore, in this work a BTA circuit has been studied and analyzed especially the effects of the input capacitance of the photodetectors.

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