

A Link Layer Analytical Model for High Speed Full-Duplex Free Space Optical Links

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Abstract

The replacement of electrical lines by free-space or guided-wave optics in high-performance digital systems is currently of active research interest. Such systems are expected to be operating in full-duplex mode delivering Gbit/s data rate in both directions. The FSO links must be robust and offer high data rate transfer not only at the physical layer but also at the upper layers.

This article lays out a systematic analysis which includes propagation delay for full-duplex outdoor FSO links using the HDLC protocol. We carry out a detailed analysis and derive the link layer throughput equation. Based on the mathematical model, we examine the link performance at high data rates with special attention on the propagation delay.

1. Introduction

The high available bandwidth, world wide license-free operation, deployment simplicity and low cost, of free-space optic systems (FSO), represent one of the most promising approaches for addressing the emerging broadband access market and its “last mile” bottleneck [1] [2]. Such robust systems, which establish communication links by transmitting laser beams directly through the atmosphere, have matured to the point that mass-produced products are now available [3]. In recent years, numerous FSO products have been set up operating at very high speeds. Available systems offer capacities in the range of 100Mbps to 2.5Gbps, and demonstration systems report data rates as high as 160Gbps [4], [5]. For such high speed links, it is important to ensure that the

upper layers can deliver the information efficiently all the way up to the application. In this paper, we focus on HDLC as the adopted link layer protocol and examine the link layer performance under varying link bit error rate.

The first significant study on the link layer performance evaluation was carried out by Bux [6] who is the precursor of subsequent studies. Barker [7], Vitsas [8], Samaras [9] and Knutson [10] extended the work by conducting their analysis on the specific area of IrDA (indoor infrared) short range links. Nevertheless, so far no systematic evaluation has been carried out for outdoor (long distance) full-duplex infrared links. Using the ARM mode of HDLC as the link layer protocol [11], we derive a mathematical model for the link layer throughput of FSO links using the concept of “window transmission time” [6]. The rest paper is organised as follows: We begin with the HDLC transmission model, followed by a detailed study leading to a derivation of system throughput. Then, a number of results are given to evaluate the system performance. Finally, we conclude the paper and give direction in further works.

2. Bidirectional HDLC Transmission Model and Parameter Definition

The most popular layer protocol used in FSO is the High-Level Data Link Control (HDLC), which has been widely implemented into products.

HDLC offers three different modes of operation [11]: Normal Response Mode (NRM), Asynchronous Balanced Mode (ABM) and Asynchronous Response Mode (ARM). NRM is the mode in which the primary station initiates transfers to the secondary station, and is only used on the simplex links. For instance, the indoor infrared IrDA link protocol IrLAP is based on NRM [12] [13]. ABM uses combined stations [11]. All combined stations are able to send and receive commands and responses without any permission from any other stations on the link. ABM is not used widely today. For ARM, the primary station does not initiate transfers to the secondary station. The secondary station does not have to wait to receive explicit permission from the primary station to transfer any frames. This mode can be used on both simplex and full-duplex links. Asynchronous Response Mode is better for point to point links, as it reduces overheads. It is widely adopted for the full-duplex links.

The analysis in this paper is carried out by using ARM mode of HDLC. Go-Back-N (GBN) scheme is selected as the automatic repeat request (ARQ) mechanism of the link [14].

Before describing the transmission model, we look at the different functionalities of the HDLC frame format:

- Information Format: The frame is used to transmit end-user data between two devices.
- Supervisory Format: The control field performs control functions such as acknowledgment of frames and requests for retransmission. It has the highest priority to be transmitted.
- Unnumbered Format: This control field format is also used for control purposes. It is used to perform link initialisation, link disconnection and other link control functions.

In order to ensure reliable transmission, each frame has a control field in the header. The control field contains the frame sequence number and the POLL/FINAL bit (P/F).

In our transmission model, Receive ready (RR) and reject (REJ) Supervision (S)-frame responses are only considered. Information (I)-frames contain a send sequence number N_s , which circles through certain values. At the end of each window, P bit is set for the last sent frame. When a full window is successfully received, the receiver sends an S-frame RR and sets the F bit. The responses RR contain a receive sequence number N_r which acknowledges the correct reception of frames up to N_r-1 , thus indicating that N_r is the next frame expected. However, if an error is found during the transmission, the receiver will send an S-frame REJ immediately to inform the transmitter for the corrupted frame retransmission. S-REJ contains a receive sequence number N_r which rejects frame N_r and thus acknowledges that correct reception of frames up to N_r-1 and indicating that N_r is the next (retransmit) frame expected. No information field is contained in S-frames, which means the length of the S-frames is the same as the frame overhead of I-frame. The link propagation delays are also considered and added in both responses. In GBN scheme, all the frames will be discarded after any frame in error is detected, and an S-frame REJ is sent to request retransmission with N_r number set to that erred frame.

The performance model we employ examines bi-directional data transmission. The transmitter has to send data frames, as well as the S-frames in order to acknowledge error or successful window transmission for the receiver side.

The link transmission model is illustrated in Fig.1 and Fig.2. Fig.1 demonstrates a 7 frames window transmission on a duplex link with two channels ATx-BRx and BTx-ARx. Fig.1 (a) illustrates error free transmission for ATx-BRx, while there is an error in frame#22 for BTx-ARx. Fig.1 (b) illustrates errors in frame#12 and 18 for ATx-BRx while there are no errors for BTx-ARx. Note that propagation time t_p is not necessarily smaller than the supervision frame time, t_s .

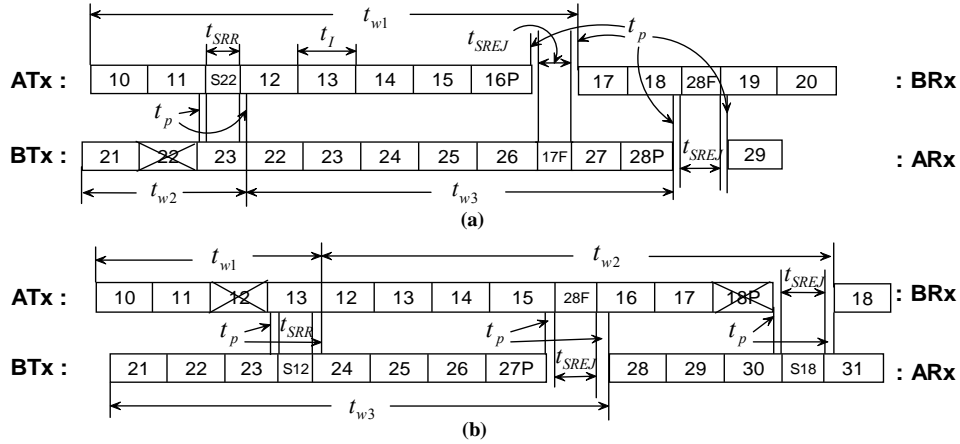


Figure 1: Window transmission of a duplex link with two channels of ATx-BRx and BTx-ARx. Where Tx stands for Transmitter and Rx stands for Receiver.

Fig.2 illustrates BTx acknowledging for an error or a successful window transmitted from ATx. In Fig.2 (a), BRx notices an error in frame#21 from ATx while BTx is transmitting frame#13 at the same time. BTx sends the REJ S-frame #21 after the end of frame#13. Fig.2 (b) illustrates BRx receiving the I-frame#21 with P bit set (final frame of the window) from ATx while BTx just started to transmit frame#13. BTx sends the RR S-frame#22 after the end of frame#13. In Fig.2 (c), BRx notices an error in frame#21 from ATx before BTx starts transmitting frame#13. BTx then sends the REJ S-frame#21 before transmitting frame #13.

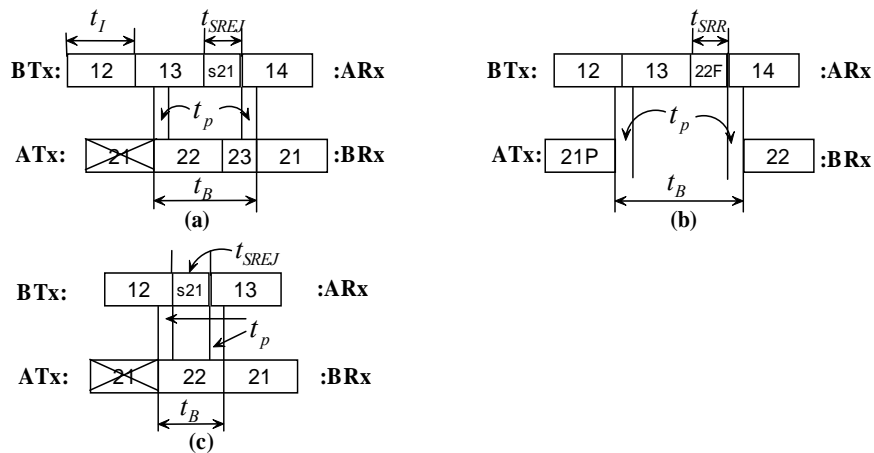


Figure 2: Acknowledgements for an error or a successful window transmission from BTx to ATx-BRx channels.

For the full-duplex links, one FSO station has both transmitter and receiver operating in parallel. However, unlike simplex infrared links [12], the station does not need to change their transmission/reception mode periodically. Therefore, no turnaround time is needed for the devices. The relevant parameters and symbols used in the analysis are shown in Table 1. t_S , t_{SRR} , t_{SREJ} , t_I , t_p and p are given by:

$$t_S = t_{SRR} = t_{SREJ} = \frac{l'}{C}, \quad t_I = \frac{l+l'}{C}, \quad t_p = \frac{d}{c} \quad \text{and} \quad p = 1 - (1 - p_b)^{l+l'}$$

According to [11], a fixed length of frame overhead $l'=72$ is taken because only high data rates are examined in this paper. Using [12] as a guide, the maximum value of window and frame sizes are 512 and 16384bit respectively.

Table 1: Parameters Used in Modelling HDLC Throughput

Symbol	Parameter Description	Unit
C	Link data rate	bit/s
d	Distance between transmitter/receiver	m
p_b	Link bit error rate	-
p	Frame error rate	-
N	Number of frames in one window (window size)	-
l	Information (I)-frame message data length (frame size)	bits
l'	Supervision (S)-frame length/ I-frame overhead	72bit
t_I	Transmission time of an I-frame	sec
t_S	Transmission time of an S-frame	sec
t_{SRR}	Transmission time of a Receive Ready (RR) S-frame	sec
t_{SREJ}	Transmission time of a Reject (REJ) S-frame	sec
t_p	Propagation time	sec
t_A	Averaged time for sending S frames per data frame.	sec
t_B	Average time spent on waiting for the S-frame	sec
t_w	Average window transmission time	sec
p_{full}	Probability of a successful full window transmission	-
D_{bl}	Throughput of ATx-BRx channel	bit/s
D_b	Throughput of either side of the full-duplex link	bit/s

3. Mathematical Modelling

In this section, we develop a mathematical model which allows derivation of link throughput for the FSO full-duplex link in the presence of bit errors. The model is derived using the concept of ‘window transmission time’ (WTT) [6]. WTT denotes the average time needed for a window transmission. It incorporates time needed for data frame transmissions, retransmission of error frames, acknowledgement S-frames, waiting time for the acknowledgements and propagation

delays. It is the average time taken from the beginning of the window's first frame transmission to the beginning of the first frame of the next window.

We assume there is always a frame ready to transmit from both directions and the frame processing time is small enough to be ignored [15]. Due to the comparatively small size of the supervision frame, we also assume S-frame transmissions for acknowledgement purposes are error free. As the assumed symmetry of the full-duplex link, study of one link direction is sufficient. Throughput of the channel consisting of transmitter A and receiver B, (ATx-BRx), as shown in Fig.1, is considered for the analysis.

For the purpose of deriving the protocol throughput, we study three different tasks of the duplex transmission separately: sending S-frames to acknowledge the other channel, waiting for the S-frames from the other channel and Information frames transmission. By considering these three protocol tasks, the transmission model is described in Fig.3 which uses the expected average time of sending S-frame t_A at the beginning of any information frame and the expected average waiting time for S-frame t_B .

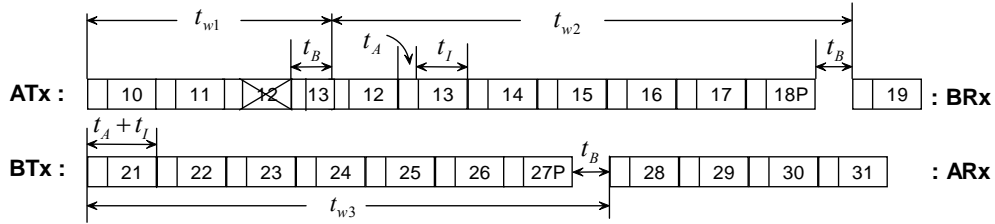


Figure 3: Use the averaged time per frame for sending S-frames t_A and average waiting time for receiving S-frames t_B to illustrate the transmission model. ATx-BRx channel: Retransmission frames due to error at I=12; BTx-ARx channel: Error free transmission of a window.

First, we consider the average time t_A consumed on sending S-frames from A to B. Due to duplicity of the link, the S-frames to acknowledge B have to be sent during data transmission, period. There are two types of S frames: S-RR which acknowledges a received error free window and S-REJ which acknowledges a frame received in error.

The probability p_{full} of error free reception of the last frame (with P bit set) of a window denoting a successful window transmission is also the probability for a transmitter to send an S-RR frame acknowledging the correct reception of a full window. By considering the probabilities

of error free reception of the first, second, to the last frame of a window being $1 - p$, $(1 - p)^2$, ..., $(1 - p)^N$ respectively, where p is the frame error rate and N is the window length, p_{full} can be derived as:

$$p_{full} = \frac{(1-p)^N}{\sum_{i=1}^N (1-p)^i} = \frac{p(1-p)^N}{(1-p)(1-(1-p)^N)} \quad (1)$$

Since the probability of a data frame being in error is p , it implies that the probability of a user sending an S-frame REJ to inform the opposite user is also p . By combining with the probability of acknowledging the correct reception of a full window p_{full} , the averaged transmit time per data frame t_A due to sending only S-frames to BTx-ARx channel is given by:

$$t_A = t_S(p + p_{full}) \quad (2)$$

The average time consumed on waiting for S-frames t_B , is given next. Two kinds of acknowledgement are expected to be received from users: S-frame RR, Fig.2 (b) and S-frame REJ, Fig.2 (a), (c). When an error or successful transmission of a window is detected, an S-frame must be sent. Due to the randomness of such events, the expected S-frame has to wait for a time slot to let BTx finish transmitting the current data frame. It is sufficient to assume the average time consumed for this time slot is half of each data frame transmission time $t_I/2$. Adding bidirectional propagation time delay $2t_p$ and S-frame transmission time t_S , the average time t_B that is needed for waiting the acknowledgement from BTx is given by (3).

$$t_B = \frac{1}{2}t_I + 2t_p + t_S \quad (3)$$

According to Fig.2 (b) and Fig.3, the window transmission time (WTT) of an error free window is given by:

$$t_N = N(t_I + t_A) + t_B \quad (4)$$

In general, when an error has occurred at the $i+1$ frame, where i is the correctly received frames, Fig.2 (a), (c) and 3, WTT is:

$$t_i = (i+1)(t_I + t_A) + t_B \quad (5)$$

The probability $p_c(i)$ of successive i correct frame transmissions followed by an error at the beginning of a window transmission is given by:

$$p_c(i) = (1-p)^i p \quad (i=1, 2, \dots, N-1) \quad (6)$$

The link throughput D_{bl} for ATx-BRx channel, which defined as the correctly transmitted information bits per second, can be derived as:

$$D_{bl} = \sum_{i=1}^{N-1} \left(\frac{i \times l}{t_i} (1-p)^i p \right) + \frac{N \times l}{t_N} (1-p)^N \quad (7)$$

The throughput efficiency for ATx-BRx channel is:

$$TPE = D_{bl} / C \quad (8)$$

The average time for transmitting one window is given by

$$t_w = \sum_{i=0}^{N-1} ((1-p)^i p t_i) + (1-p)^N t_N \quad (9)$$

Due to symmetry of the link, the above analysis is also holds true for ATx-BRx channel's twin channel BTx-ARx. Therefore, throughput of either side of the full-duplex link is $D_b = D_{bl}$.

4. Link Performance at High Data rate Transmission

Based on the mathematical analysis and using equation (7), the link performance of the system is studied in this section. Using BER and data rate as parameters, with values 10^{-6} , 10^{-5} and 10^{-4} , and 2.5Gbps respectively, throughput comparisons are carried out using two different combinations of window and frame sizes with values of $N=512$, $l=16$ kbit and $N=7$, $l=5$ kbit. Link throughput efficiency is plotted against link distance in the range of 100m to 10km in Fig.4.

The link when operated at low BER generally has, as expected, larger throughput. The throughput efficiency decreases as the link distance increases as it is apparent in all curves. The propagation time t_p which is proportional to the link distance has considerable effect on the link throughput for long distance links for both combinations of window and frame sizes especially when the BER is low, $p_b=10^{-6}$. However, t_p has different effect on throughput when using different N and l combinations. For instance, nearly 70% throughput reduction occurs at the distance of 10km when $N=7$ and $l=5$ kbit for $p_b = 10^{-6}$, while t_p has much smaller effect on the throughput when $N=512$ and $l=16$ kbit in the same BER, Fig.4. Because RR S-frames have to be sent frequently while small N and l values are used, the time for waiting for the S-frame RR becomes large when the link distance is large (t_p is large). Therefore, the transmitter waits a long time for

the acknowledgement from the receiver before starting a new window transmission. Large N and l values therefore have better throughputs for the long distance links. However, errors are more likely to occur when frames are large ($l=16\text{kbit}$), and longer time period is required on waiting for the REJ S-frames. Small N and l therefore have better throughput while the link distance is short (t_p is small). For the same BER, the crossing points of the two curves that represent different N and l combinations imply a better throughput may achieve by appropriate adaptation of window and frame size.

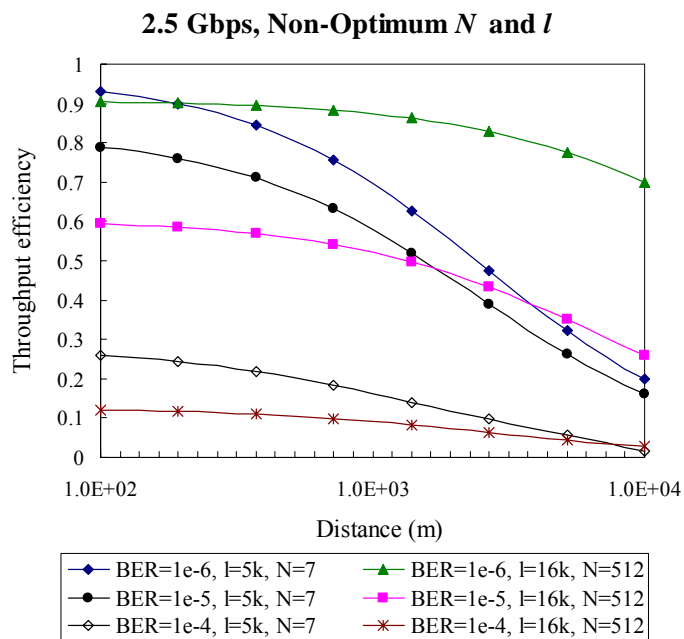


Figure 4: Link throughput in varies BERs for the distance range from 100m to 10km.

5. Conclusion and Future Work

Motivated by the fast developing free-space optical technology, and in order to examine and improve the performance of the popular duplex HDLC link layer protocol over FSO links, a systematic mathematical model for high speed full-duplex FSO links is presented in this paper using the ARM mode of HDLC as the link layer protocol. A simple throughput formula is derived from the model in the presence of bit error rate. Based on the analytical model, we then studied the link performance and the effect of propagation time on link throughput. The result shows that the

propagation time has a significant effect for long distance links, and the effect is likely to be even more severe if higher data rates are applied in future systems. As a pair of inappropriate window and frame size will have a significant detriment on the system throughput, an area worth further study is to investigate the optimum value of window and frame size to acquire the maximum throughput for the system.

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