Throughput Analysis of the IrDA IrLAP Optical Wireless Link Access Protocol

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Abstract

A performance analysis of the optical wireless IrDA data link layer access protocol (IrLAP) is presented. Three different mathematical approaches are presented to model the throughput of the IrDA IrLAP protocol. All methods are leading to the same simple equation for the throughput at this layer. The analyses are based on evaluation of window transmission time, probability of correct frame transmission and virtual transmission time respectively. Mathematical model results are compared and validated with simulation results obtained using OPNET modeller.

I. INTRODUCTION

Recent demand for wireless connectivity in laptop, palmtop computing and peripheral devices has led to the development of optical wireless links suitable for such applications. Infrared (IR) transmission medium is widely used for indoor wireless data communication as it provides short range links of high bandwidth at low cost, within an unregulated optical spectrum. Infrared components are of low cost and require low power consumption. Since infrared beam cannot penetrate through walls, infrared spectrum reuse can be used within buildings and provided the IR beam is narrow, can be used within rooms as well without significant interference.

The IrDA standard provides half-duplex point-to-point connectivity with data rates up to 115.2 Kbps using standard serial interface or up to 4 or 16 Mbps with the high speed extensions [1], [2].

IrLAP, the data link layer of the IrDA protocol, is an HDLC derivative. IrLAP is based on the HDLC protocol operating in NRM mode. It supports communication between nodes by assigning a primary and a secondary node. Role assignment takes place during link establishment. If more than two stations are involved in data exchange, all traffic passes through the primary. The primary gives permission to the secondary to transmit by setting the P/F bit of the last frame it transmits, thus reversing the link direction. When the secondary finishes transmission, it returns control to the primary again by setting the P/F bit in the last frame transmitted.

Performance analysis of IrLAP using the concept of virtual transmission time is given in [3] following the HDLC performance analysis model given in [4]. Two new and simpler mathematical models are developed here for the performance analysis of IrLAP. They use the concept of window transmission time and probability of correct frame transmission respectively. The existing model using virtual transmission time is also presented for completeness and compared with the introduced models. Key differences in model development are explained. All three methods converge to the same equation for IrLAP throughput.

II. BRIEF DESCRIPTION OF IRLAP PROTOCOL AND PARAMETER DEFINITIONS

The performance models in this work consider data transfer from primary to secondary nodes. It is assumed that the primary has always information ready for transmission. Information frames (I-frames) from the primary station with maximum size of 16Kbits carry information to the secondary station which responds only with supervisory frames (S-frames) acknowledging frames received correctly.

We consider only RR and REJ S-frame responses. The I-frame contains a send sequence number Ns, which circles through values from 0 to 7 for speeds up to 4Mbps and values from 0 to 127 for 4Mbps and 16Mbps. S-frame RR responses contain a receive sequence number, Nr, which acknowledges the correct reception of frames up to Nr-1, thus indicating that Nr is the next frame expected. The S-frame REJ responses a contain receive sequence number Nr which rejects frame Nr. Thus acknowledges the correct reception of frames up to Nr-1, thus indicating that Nr is the next (retransmitted) frame expected. Both responses reverse the link direction by setting the P/F bit.

The parameters used in the mathematical analysis are shown in Table I.

TABLE I
PARAMETERS USED IN MODELLING IRLAP THROUGHPUT

Symbol	Parameter Description	Unit
C	Link data baud rate	bits /sec
p_b	Link bit error rate	-
p	Frame error probability	-
l	I-frame message data length	bits
l'	S-frame length / I-frame overhead	bits
t_I	Transmission time of an I-frame	sec
t_S	Transmission time of an S-frame	sec
t_{ta}	Minimum turn-around time	sec
t_{ack}	Acknowledgement time	sec
T_{max}	Maximum turn-around time	sec
t_{Fout}	F-timer Time-out period	sec
D_f	Frame throughput	frames/sec
D_b	Data throughput	bits/sec

The values for t_S , t_I , t_{ack} , p and D_b are given by:

$$t_S = \frac{l'}{C} \qquad (1)$$

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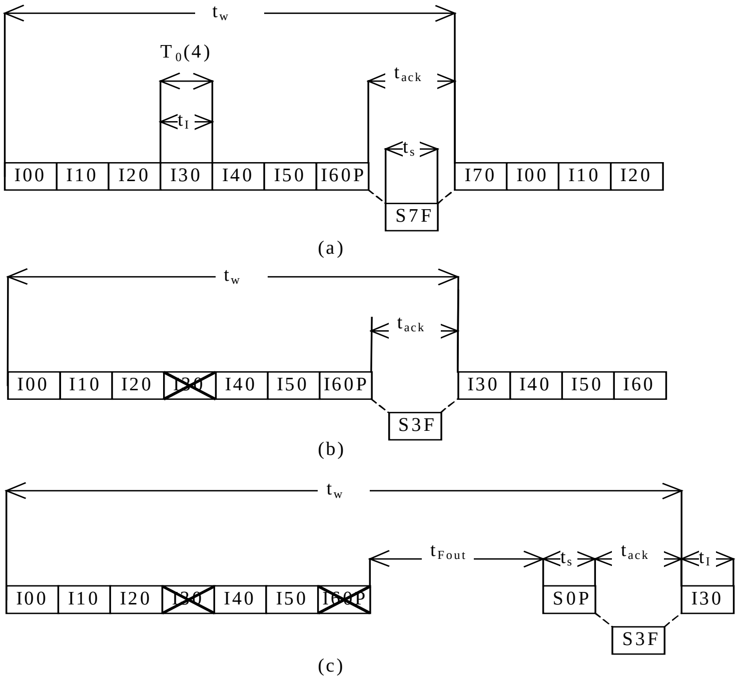

Fig 1. Evaluation of window transmission time (a) Window error free transmission (b) Retransmitted frames due to error frame at *w* = 4 (c) Retransmitted frames and F-timer delay due frame error at w = 4 and w =1

$$t_I = \frac{l+l'}{C} \tag{2}$$

$$t_{ack} = 2t_{ta} + t_S \tag{3}$$

$$p = 1-(1-p_b)^{l+l'} \tag{4}$$

$$D_b = lD_f \tag{5}$$

Window size *N* is the maximum number of unacknowledged frames that the transmitter can transmit. Maximum window size parameter, $W_{\max}$, is negotiated and agreed between the two stations during link establishment. However, the maximum time a station can hold the link, $T_{\max}$, combined with data rate and packet size may limit the number of consecutive frames a station can transmit. Thus, *N* is given by

$$N = min\left\{W_{\max}, floor\left(\frac{T_{\max}}{t_I}\right)\right\} \tag{6}$$

where *min* is ‘the lesser of’ and *floor* is ‘the largest integer not exceeding’.

In the case considered here, the transmitter always has a data packet ready for transmission. As a result, a window of *N* frames will be transmitted before the link direction is reversed. The last data packet in the window has the P bit set forcing the receiving station to respond. The receiver awaits a specific amount of time t_{ta}, to cope with hardware latency and transmits a RR or REJ response indicating the next data frame expected or the frame received in error respectively. The transmitter then determines the number of consecutive frames in the beginning of the previous window received correctly and repeats the remaining frames in the next window followed by new frames to form a complete *N* frame transmission. If the last frame in a window is not correctly received, the receiver does not respond as the P bit is lost. The transmitter awaits for F-timer expiration and sends a RR forcing the receiver to respond. RR and REJ frames are considered small enough to be error free.

III. MATHEMATICAL MODELLING OF IRLAP PROTOCOL

In this section we develop three independent methods for the throughput of IrLAP, all converging to the same simple equation for throughput.

A. Window transmission time method

This mathematical model uses the concept of the “window transmission time” (WTT) to denote the average time needed for a complete window transmission. WTT denotes the average time taken from the beginning of window’s first frame transmission to the beginning of next window’s first frame transmission. WTT incorporates time needed for frame transmissions and acknowledgements and delays for reversing the link.

If the last frame in sequence is correctly received, as shown in Fig. 1.(a) and 1.(b), window transmission time t_w, is given by

$$t_w = Nt_I + t_{ack} \tag{7}$$

If the last frame in sequence is not correctly received, the P bit is lost and the receiver fails to respond with an acknowledgement as it does not know that it can now transmit. Primary awaits until the F-timer has expired and sends a RR S-frame forcing the receiver to respond as shown

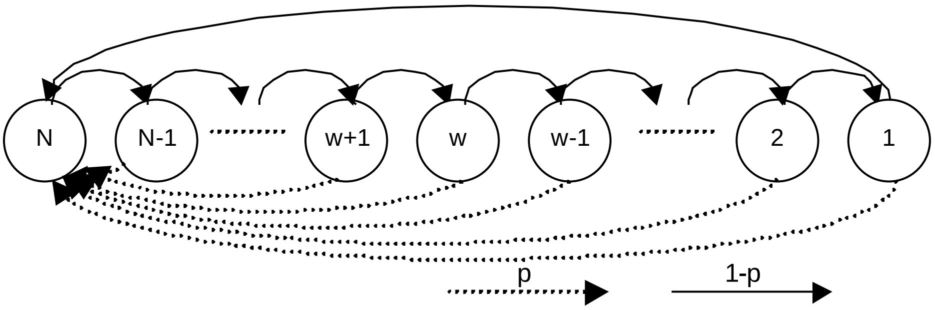

Fig 2 State transition diagram of the window width process for the mathematical model that uses the probability of correct frame transmission.

in Fig. 1(c). This situation incorporates an additional delay of $t_{Fout} + t_s$ and WTT is given by

$$t_w = Nt_I + t_{Fout} + t_s + t_{ack} \tag{8}$$

As the last frame in sequence is lost with probability *p*, the average window transmission time is given by

$$t_w = Nt_I + p(t_{Fout} + t_s) + t_{ack} \tag{9}$$

Considering that correct frame transmissions following an erroneous frame transmission in the same window are considered out of sequence and have to be retransmitted, the probability $p_c(w)$ of successive *w* correct frame transmissions followed by an error at the beginning of a window transmission is given by

$$p_c(w) = (1-p)^w p\,,\ \ w=1,2,\dots,N\text{-}1 \tag{10}$$

The probability that all frames in a window are correctly transmitted is

$$p_c(N) = (1-p)^N \tag{11}$$

The number of frames correctly transmitted in one window transmission p_{all} is

$$p_{all} = \sum_{w=1}^{N} w p_c(w), w=1,2,\dots,N \tag{12}$$

The frame throughput D_f can now be calculated by dividing the number of frames correctly transmitted in one window transmission p_{all} by the average time needed for this window transmission t_w.

$$D_f = \frac{\sum_{w=1}^{N} w p_c(w)}{Nt_I + p(t_{Fout} + t_s) + t_{ack}} \tag{13}$$

Considering that

$$\sum_{w=1}^{N} w p_c(w) = \sum_{w=1}^{N-1} w(1-p)^w p + N(1-p)^N =$$
$$= \frac{(1-p)\left(1 - N(1-p)^{N-1} + (N-1)(1-p)^N\right)}{(1-(1-p))^2} p + N(1-p)^N =$$
$$= \frac{(1-p)\left(1-(1-p)^N\right)}{p} \tag{14}$$

equation (13) for the IrLAP throughput finally becomes

$$D_f = \frac{1-p}{p} \frac{\left(1-(1-p)^N\right)}{Nt_I + p(t_{Fout} + t_s) + t_{ack}} \tag{15}$$

B. Probability of correct frame transmission approach

This mathematical model uses the concept of the probability of a correct frame transmission (PCFT) and the position of that frame in a window transmission. A frame transmission sees window *w* if *w* frames (including the frame in question) are transmitted before the transmitter has to stop transmitting because of *N* unacknowledged frames. The PCFT seeing a window *w*, is defined as the probability of a frame transmission seeing a window *w*, provided that the previous I-frame in the same window either does not exist or is received in sequence and without error. In simple words PCFT is the probability of a frame transmission seeing a window *w* in sequence and that once the frame is correctly received, it will not have to be retransmitted. Please note that correctly received frames out of sequence are discarded and have to be retransmitted.

The window width process can be considered as a Markov chain and correct frame transmission probabilities can be calculated from the state transition diagram shown in Fig.2. Every time an I-frame is correctly received the window width is reduced by one until it reaches its minimum value of one, which represents the last frame in a window transmission. If a frame transmission error occurs, *w* returns to its maximum value N as frames transmitted in the same window after the lost frame do not comply with the definition of PCFT as they are received out of sequence. Transitions from state 1 to state *N* can be justified as follows. After the last frame in a window is transmitted, link direction is reversed and the receiver acknowledges the number of frames correctly received. Thus, regardless of the correctness of the last frame transmission, the window opens again and the first frame in the new window is always transmitted in sequence.

Probabilities in Fig.2 are calculated by

$$\phi(w) = \frac{p(1-p)^{N-w}}{1-(1-p)^N}\,,\ \ w=1,2,\dots,N \tag{16}$$

The number of frames correctly received can now be found by multiplying the PCFT seeing window *w* by the probability that the frame is correctly received, 1-*p*. Thus the probability of correct frame reception *q* is given by

$$q = \sum_{w=1}^{N} \varphi(w)(1-p) \tag{17}$$

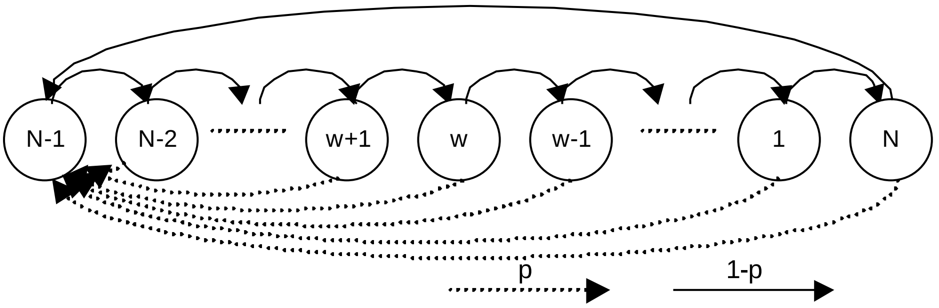

Fig 3 State transition diagram of the window width process for the mathematical model that uses the virtual transmission time.

The time expectation, $E(t)$, of the time needed to transmit all frames with PCFT seeing all possible windows w is the time needed to transmit $\varphi(N)$ windows of frames ($\varphi(w) <= \varphi(N)$, $w=1,2,\ldots,N-1$). The average time needed for a window transmission t_w is given by (9) and

$$E(t) = \varphi(N)t_w \tag{18}$$

Frame throughput D_f is thus given by

$$D_f = \frac{q}{E(t)} = \frac{\sum_{w=1}^{N} \varphi(w)(1-p)}{\varphi(N)t_w} \tag{19}$$

Considering that

$$D_f = \frac{\sum_{w=1}^{N} \varphi(w)(1-p)}{\varphi(N)t_w} = \frac{\sum_{w=1}^{N} \frac{p(1-p)^{N-w}}{1-(1-p)^N}(1-p)}{\frac{p}{1-(1-p)^N}t_w}$$

we derive

$$D_f = \frac{1-p}{p} \frac{\left(1-(1-p)^N\right)}{Nt_I + p(t_{Fout} + t_s) + t_{ack}} \tag{20}$$

which, of course, is identical to (15).

C. Virtual transmission time analysis

This mathematical model uses the concept of “virtual transmission time” (VTT) of a frame to calculate the frame throughput. VTT of a frame begins at the end of the previous frame transmission provided that this previous frame is received in sequence and without transmission error. It terminates at the end of the frame’s transmission provided that this transmission is successful. In other words, VTT represents the time between in-sequence packet arrivals. Frame throughput can be calculated as the reciprocal of the average VTT of received frames. A detailed analysis can be found in [3] which follows a similar analysis in [4] for the HDLC protocol.

We denote $t_v(w)$, the mean virtual transmission time of I-frames seeing window width W equals w, and $f(w)$, the probability that W equals w. The mean virtual transmission time can be calculated by

$$t_v = \sum_{w=1}^{N} f(w)t_v(w) \tag{21}$$

Mean VTT $t_v(w)$, incorporates delays caused by possible (one or more) erroneous frame transmissions of a frame initially seen window w. Thus $t_v(w)$ is calculated by the addition of the time needed for the initial frame transmission and the time needed for subsequent frame retransmissions multiplied by the probabilities that these transmissions are required

$$t_v(w) = T_0(w) + \sum_{n=1}^{\infty} P_n E[T_n(w)] \tag{22}$$

where $T_0(w)$ is the time needed for the initial frame transmission seeing window w, P_n is the probability that the nth transmission is required and $E[T_n(w)]$ is the time expectation required for the nth retransmission.

According to [3]

$$T_0(w) = \begin{cases} t_I & w \neq N \\ t_I + t_{ack} & w = N \end{cases} \tag{23}$$

$$P_1 = p$$

$$E[T_1(w)] = \begin{cases} (w-1)t_I + p(t_{Fout} + t_S) + t_{ack} + t_I & w \neq 1 \\ t_{Fout} + t_S + t_{ack} + t_I & w = 1 \end{cases} \tag{24}$$

$$P_n = p^n \quad n \geq 2 \tag{25}$$

$$E[T_n(w)] = T_2 \quad n \geq 2 \tag{26}$$

$$T_2 = Nt_I + p(t_{Fout} + t_S) + t_{ack} \tag{27}$$

and finally

$$t_v(w) = T_0(w) + pE[T_1(w)] + \frac{p^2}{(1-p)}T_2 \tag{28}$$

Probabilities $f(w)$, of a frame seeing window w at the beginning of its virtual transmission time, should be calculated using Fig. 3. Transitions from any state w to state N-1 with probability p are justified as follows. After an erroneous in sequence frame transmission, the frame is retransmitted at the beginning of next full window transmission. If the retransmission is again itself in error, the frame is retransmitted at the beginning of the following window transmission, and so on. As the virtual transmission time of the initial’s frame transmission is still being calculated and ends at the end of correct frame’s transmission, the next in sequence frame transmission is the second frame in the window transmission thus seeing window N-1.

Differences between Fig. 3 and Fig. 2. are justified as follows. After a frame transmission error, the frame is retransmitted at the head of the next window. The retransmission sees always window N and is transmitted in sequence. As Fig. 2 shows the window width process of in-sequence frame transmissions, p-arrows representing frame transmission errors contribute to state N for every frame transmission error. According to its definition, Fig. 3 represents the window width process of frame transmissions provided the previous frame is transmitted in sequence and error free. Thus, if a frame encounters one or more transmission errors, it will eventually be transmitted correctly at the head of a window transmission. Thus, as the next frame transmission sees a window N-1, p-arrows in Fig. 3, representing one or more transmission errors of the same frame, contribute to state N-1.

Considering the state transition diagram in Fig.3 probabilities $f(w)$ are determined as follows:

$$f(w) = \frac{p(1-p)^{N-w-1}}{\left(1-(1-p)^{N}\right)}, \quad w=1,2,\ldots,N\text{-}1 \text{ and}$$

$$f(N) = \frac{p(1-p)^{N-1}}{\left(1-(1-p)^{N}\right)} \tag{29}$$

Considering that

$$D_f = \frac{1}{t_v} \tag{30}$$

and combining equations (21), (28), (29) and performing algebraic calculations, we arrive at

$$D_f = \frac{1-p}{p} \frac{\left(1-(1-p)^{N}\right)}{Nt_I + p\left(t_{Fout} + t_s\right) + t_{ack}} \tag{31}$$

IV. MODEL VALIDATION

To validate results from the above mathematical models, a set of simulation runs using OPNET™ [5] were performed using different link parameters. The results showed confidence interval of 98% were compared with those obtained from the mathematical analysis.

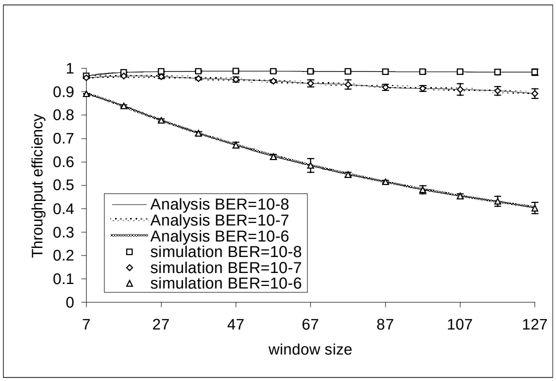

Fig. 4. Throughput against window size for 16Mbps link. l= 16384 bits, W_{max}=500ms, t_{ta} = 0.1ms. Simulation confidence interval=98%.

Fig. 4 shows throughput efficiency versus window size for different BERs for a 16Mbps link with t_{ta}=0.1ms, packet size l=16Kbits and $W_{\max}$=500ms. A good agreement with simulation results is observed. Throughput efficiency degrades with the increase of window size for high BERs while it is increased with the increase of window size for low BERs. Fig. 5 shows throughput efficiency versus BER for a 16Mbps link with packet data size l=16Kbits, $W_{\max}$=500ms, t_{ta}=1ms and window sizes 7 and 127. The plot obtained from the mathematical analysis shows an agreement with points obtained from simulation results.

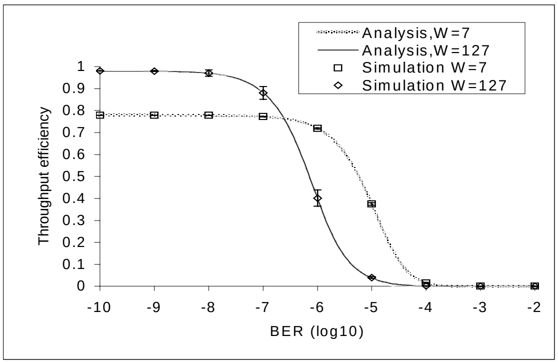

Fig. 5. Throughput against BER for 16Mbps link. l= 16384 bits, W_{max} =500ms, t_{ta} =1ms. Simulation confidence interval=98%.

V. CONCLUSIONS

We have shown that a simple closed form equation can be derived for the throughput of IrLAP using three different mathematical approaches, namely the concept of window transmission time, the correct frame transmission probability and the virtual transmission time. The simple formula is easier to compute and allows better intuitive understanding of the throughput. Saturation throughput dependency on variations of various link parameters is very easy as saturation throughput is now calculated using a simple equation. The mathematical modelling results have been verified using the OPNET modeller.

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