IrDA IrLAP Protocol Performance and Optimum Link Layer Parameters for Maximum Throughput

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Abstract-- **Infrared ports are employed in a wide variety of devices ranging from personal computers and printers to mobile phones. Infrared connectivity complies to specifications defined by Infrared Data Association (IrDA). The performance of IrDA links may be measured at the IrLAP data link layer, which controls the IrDA hardware. A simple equation to calculate throughput from different link parameters is derived by calculating the average window transmission time. Throughput analysis results are presented that reveal the significance of link layer parameters, such as window and frame size, and physical layer parameters, such as minimum turn around time. Simple equations for the optimum values for window size and/or frame length are derived by differentiating the throughput equation. These values maximise throughput performance for different BER values. Simulation results indicate that optimum window and frame size implementation results in significant throughput increase even for high BER.**

I. INTRODUCTION

The development of Infrared Data Association (IrDA) optical wireless links as an industry standard has led to a plethora of IrDA infrared ports in computers of all sizes and in peripherals. Personal computers, personal digital assistants (PDAs), digital cameras, mobile phones and printers are examples of devices utilising IrDA links. Over 40 million devices with infrared ports are manufactured each year following standards defined by IrDA[1]. Digital representation of information is expanding to new devices such as video and cameras. New devices have "computer like" capabilities for storing and retrieving information such as cell phones and PDAs. Optical wireless and the IrDA standard offer a means for all these devices to communicate with each other in a wireless manner. IrDA specifications for infrared communications play an important role in short-range communications. IrDA connections replace communication cables and eases point to point user information exchange.

The IrDA physical layer is controlled by a link layer protocol, IrLAP [2], which is an HDLC derivative. The performance of IrDA optical wireless links may be measured by the throughput, which can be drawn at the IrLAP layer. Performance analysis of IrLAP using the concept of virtual transmission time is given in [3] following a HDLC performance analysis model given in [4]. However, there has been no simple closed form formula available to date, which allows us to have an intuitive understanding of the performance of such links. Such equation relating all the important variables linking to throughput at the IrLAP layer would be very valuable for designers and implementers of such links.

This paper presents an analytical model for the IrLAP saturation throughput performance assuming random transmission errors. The model is validated by comparing simulation with analytical results and is employed to study the effect of physical and link layer parameters on IrLAP performance. We also discuss the effectiveness of physical and link layer parameters on the IrDA link data rate increase, which took place over the past few years. By setting the first derivative of the throughput equation equal to zero, simple equations for optimum values for window and/or frame size that maximize throughput are derived. Finally, our analytical and simulation results agree on throughput improvement when optimum values are implemented.

II. DESCRIPTION OF IRLAP PROTOCOL AND PARAMETER DEFINITIONS

IrLAP is the data link layer in IrDA protocol stack. It facilitates the interconnection of devices using a directed half duplex serial infrared link as defined in IrDA physical layer [5]. It assigns primary and secondary roles to devices during link establishment. IrLAP supports one primary and one or more secondary stations to facilitate communication between multiple stations. All information traffic passes through the primary station. The present work is limited to the interconnection of two devices, a primary and a secondary node.

IrLAP frames consist of an 8-bit address field, an 8-bit control field and a variable length information field [1][2][6]. The control field contains an identifier, which determines the frame type. Unnumbered frames (U-frames) are used in establishing and disconnecting links and in reporting procedural errors. Supervisory frames (S-frames) assist in the transfer of information although S-frames never carry information data. S-frames are used to acknowledge correctly received frames, report frame sequencing errors and convey ready or busy conditions. Information frames (I-frames) carry information data across the link. Depending on frame type, the control field may contain a send sequence number, Ns, used to number the frames sent. It may also contain a receive sequence number, Nr, used to number frames correctly received. Valid Ns and Nr values are from 0 to 7. The control field size is extended to 16-bit for the 4Mbit/s and the 16Mbit/s link data rate to accommodate send and receive sequence numbers from 0 to 127. The control field also contains the P/F bit, which is used to transfer transmission control. When it is used by the primary, it is the poll (P) bit, which is used to solicit a response or a sequence of responses from the secondary. When used from the secondary station it is the final (F) bit, which indicates the last frame transmitted, as a response to

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TABLE I
PARAMETERS USED IN MODELLING IRLAP THROUGHPUT

Symbol	Parameter Description	Unit
C	Link data bit 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_{Imax}	Transmission time of an I-frame with l=16Kbits	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
W_{max}	Maximum window size	frames
N	Window size	frames
D_f	Frame throughput	frames/sec
D_b	Data throughput	bits/sec

the previous poll command.

The performance model we employ examines data transfer from primary to secondary nodes. We assume the saturation case, where the primary always has information ready for transmission. I-frames carry data from primary to secondary station. Since the secondary does not transmit information to the primary, it responds only with S-frames with the F bit set, acknowledging frames received correctly and reversing link direction.

The parameters used in mathematical analysis are shown in Table I. The values for t_S, t_I, t_{ack}, p and D_b are given by:

$$t_S = \frac{l'}{C} \tag{1}$$

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

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

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

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

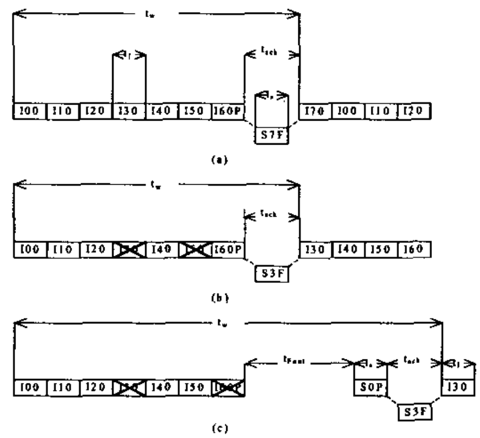
Window size N is the maximum number of unacknowledged frames that the transmitter can transmit. Its maximum value is 7 for link rates up to 4Mbit/s and 127 for the 4Mbit/s and 16Mbit/s links. Maximum window size parameter, W_{max}, is negotiated and agreed between the two stations during link establishment. However, the maximum time a station can hold the link, T_{max}, combined with data rate and frame size may limit the number of consecutive frames a station can transmit as it has higher priority over the agreed window size and frame size [2]. 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'.

III. MATHEMATICAL MODELLING OF IRLAP PROTOCOL

Our model evaluates the average window transmission time



Ixy : I-frame with N_s=x and N_r=y
IxyP : I-frame with N_s=x,N_r=y and P-bit set
SxP : S-frame with N_r=x and P-bit set
SxF : S-frame with N_r=x and F-bit set

Fig. 1. (a) Window error free transmission (b) Retransmitted frames due to error frame at Ns=3 and Ns=5 (c) Retransmitted frames and F-timer delay due frame error at Ns=3 and Ns=6.

(WTT), which is the average time needed for a complete window transmission. WTT denotes the average time taken from the beginning of the window's first frame transmission to the beginning of next window's first frame transmission. WTT incorporates time needed for frame transmissions and acknowledgements, delays for reversing the link and timer time outs.

As shown in Fig 1.(a) and 1.(b), if the last frame in a window transmission is correctly received and regardless of the number of frames received in error in this particular window, WTT t_w, is given by

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

If the last frame in the sequence is not correctly received, the P bit is lost and the receiver does not respond as it is unaware of link reversion. The primary waits for an F-timer expiration and sends a RR S-frame forcing the receiver to respond as shown in Fig. 1.(c). Assuming that the S-frames are always received correctly, the P bit loss 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

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

IrLAP implements a Go-Back-N Automatic Repeat Request scheme. This scheme considers correct frames following an erroneous frame in the same window as being out of sequence and retransmits them. The probability $p_c(w)$ of w successive correct frame transmissions followed by an error at the beginning of a window transmission is given by

$$p_c(w) = (1-p)^w p,\ w=0,1,2,\ldots,N\text{-}1 \tag{10}$$

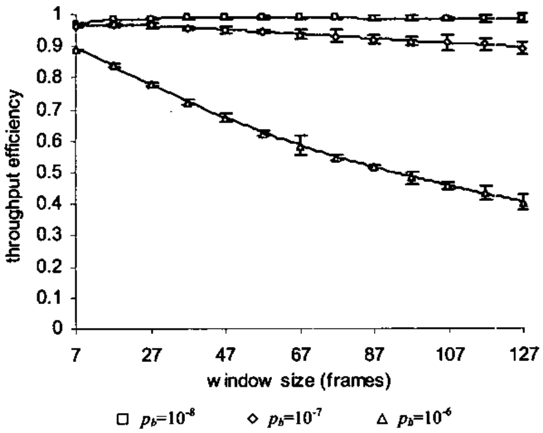


Fig. 2. Analysis versus simulation: Throughput efficiency against window size, C=16 Mbit/s, l= 16Kbits, T_{max}=500ms, t_{ta} =0.1ms. Simulation confidence interval=98%.

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

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

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

$$p_{all}=\sum_{w=0}^{N} w p_c(w) \tag{12}$$

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

$$D_f=\frac{p_{all}}{Nt_I+p(t_{Fout}+t_s)+t_{ack}} \tag{13}$$

Finally

$$D_b=l\,\frac{(1-p)}{p}\,\frac{\left(1-(1-p)^N\right)}{\left(Nt_I+p(t_{Fout}+t_s)+t_{ack}\right)} \tag{14}$$

Equation (14) indicates that data throughput D_b can be calculated by multiplying frame length l with the expected number of correct in sequence frames in a window transmission {= $(1-p)(1-(1-p)^N)/p$ } divided by the average window transmission time t_w.

IV. Model Validation

To validate the above mathematical model, a set of simulation runs was performed using the OPNET™ simulation package [7]. Our OPNET simulator emulates IrLAP station behaviour as close as possible, including transmission times, turn around delays, transmission errors and timer expiration.

Fig. 2 plots throughput efficiency versus window size for different bit error rate (BER) p_b values. The analytical model is validated as its calculated throughput efficiency (lines) practically coincides with simulation results (points). Simulation results are obtained with a confidence interval of 98%.

TABLE II
Nt_I AND t_{ack} FOR SIR AND FIR DATA RATES

specification	data rate	year	W_{max}	N	Nt_I (ms)	t_{ta} (ms)	t_{ack}(ms)
SIR	115.2 Kbit/s	1994	7	3	427.9	10	20.00
FIR	576 Kbit/s	1995	7	7	199.7	10	20.00
FIR	1.152 Mbit/s	1995	7	7	99.8	10	20.00
FIR	4 Mbit/s	1995	7	7	28.8	10	20.00
VFIR	4 Mbit/s	1999	127	121	497.8	10	20.00
VFIR	16 Mbit/s	1999	127	127	130.6	0.1	0.20

V. Throughput Analysis

Equation (14) gives an intuitive understanding of IrLAP throughput performance. The average WTT given by eq. (9) consists of three factors. Factor Nt_I represents the I-frame transmissions that carry payload data, factor $p(t_{Fout}+t_s)$ considers the delay introduced by P bit loss and t_{ack} represents the delay for reversing link direction. For very low BERs, factor $p(t_{Fout}+t_s)$ is very small as the P bit is seldom lost. Table II shows the remaining two factors for the IrPHY data rate evolution. Ir-PHY ver 1.0 Serial Infrared (SIR) specification [8] defined data rates up to 115.2 Kbit/s using standard serial hardware, Ir-PHY ver 1.1 Fast Infrared (FIR) specification [9] extended data rates up to 4Mbit/s and, finally, Ir-PHY ver 1.3 Very Fast Infrared (VFIR) specification [10] added the 16Mbit/s link rate. Table II presents the data rate(s) introduced by new specifications, the year the new specification was published, specification's maximum window size, the maximum window size that can be enforced for 16Kbit frames within T_{max} (N), specification's maximum t_{ta} value and the two main factors that contribute to WTT for low BER. Table II reveals that although FIR defined much higher rates (up to 4Mbit/s), it did not define a lower maximum t_{ta} value for FIR IrDA ports. As a result, the time utilized for I-frame transmissions dropped from 427.9 ms to 28.8 ms but the time utilized on reversing link direction twice, was kept constant at 20 ms as t_{ta} value was unchanged. As a result, 4Mbit/s IrDA links employing the maximum allowed t_{ta}=10ms took 20ms for acknowledgements for every 28.8ms of data transmission! Fig. 3 plots throughput efficiency versus BER for SIR and FIR link rates with t_{ta}=10ms, W_{max}=7 and l=16Kbits. Throughput efficiency decreases with data rate increase as link turn around frequency is increased. As a result a maximum throughput efficiency of 0.59 can be achieved for 4 Mbit/s links.

VFIR specification, along with introducing the higher 16Mbit/s rate, addressed the problem by reducing t_{ta} to 0.1 ms and by optionally increasing window size to 127 frames for 16Mbit/s links. The specification also introduced an optional window size increase to 127 frames for the existing 4Mbit/s links in an effort to solve the existing problem. Fig. 3 plots throughput efficiency versus link BER for 4 Mbit/s links with t_{ta}=10ms, l=16Kbits and a window size of 127 frames. Throughput significantly increases with the 127 window size

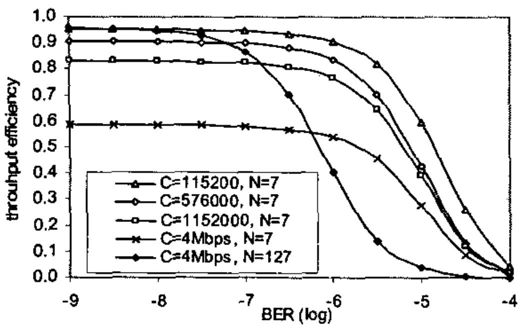


Fig. 3. Throughput efficiency versus BER for t_{ta}=10ms, l=16Kbits

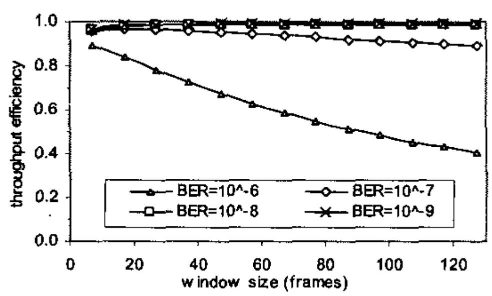


Fig. 4. Throughput efficiency versus window size for C=16Mbit/s, t_{ta}=0.1ms, l=16Kbits

employment and reaches a very good value of 0.96.

Fig. 4 plots throughput versus window size for different link BERs for 16Mbit/s links. Window size increase results in slight throughput increase for low BERs and significant decrease for high BERs. For large window size values, significant throughput decrease is observed for BER values higher than 10^{-7} caused by the retransmission of correctly received out of sequence frames. This is a limitation of the IrDA Ir-LAP protocol when non-optimum window size is used at high BER. Fig. 5 plots throughput efficiency versus frame size for 16Mbit/s links with t_{ta}=0.1 ms and W_{max}=127. It shows that, although for low BER the maximum frame size should be used, a much different frame size value should be used for high BER for maximum throughput. Thus, optimum window size and frame size parameters are of great importance for Ir-LAP throughput.

VI. Optimum Link Parameter Values

Equation (14) is very simple and allows extraction of optimum values for certain link layer parameters analytically. The t_{Fout} value implemented in the current work is $t_{Fout}=t_{lmax}+2t_{ta}$. This t_{Fout} value corresponds to a maximum window size parameter of value one for secondary station negotiated and agreed during link establishment.

A. Optimum Window Size

In order to derive the optimum values for different link parameters, (14) is differentiated and set to zero. By taking the valid approximation for small p,

$$(1-p)^N \approx 1 - Np + \frac{N(N-1)}{2}p^2 \qquad (15)$$

after some algebra

$$N_{opt} = \sqrt{\frac{2t_{ack}}{t_l p}} \qquad (16)$$

and considering that for $l >> l'$, $p \approx lp_b$ and $t_l \approx \frac{l}{C}$ we derive

$$N_{opt} = \sqrt{\frac{2t_{ack}C}{l^2 p_b}} \qquad (17)$$

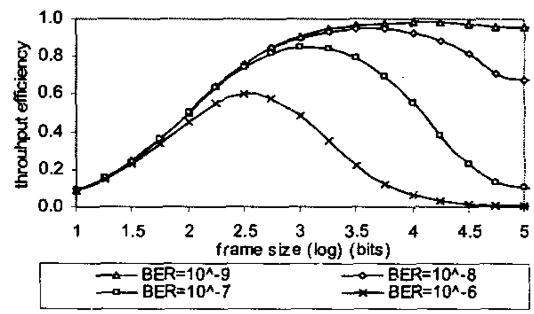


Fig. 5. Throughput efficiency versus frame size for C=16Mbit/s, t_{ta}=0.1ms, W_{max}=127

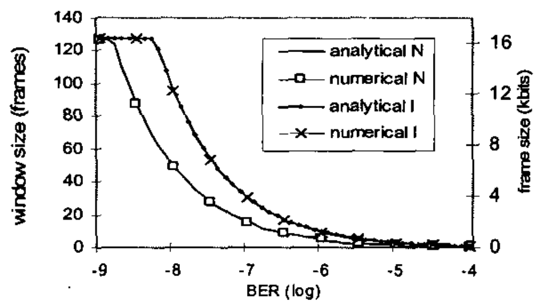


Fig. 6. Optimum value comparison, C=16Mbit/s, t_{ta}=0.1ms

Fig. 6 shows the optimum window size versus BER for fixed frame size l= 16Kbits. As the BER increases, the optimum window for best throughput decreases. Fig. 6 compares analytical N_{opt} values obtained from (17) with N_{opt} values obtained using exact numerical methods in throughput equation (14). A very good match is observed and the approximations used to derive (17) are validated.

B. Optimum Frame Size

Considering that a single bit transmission error causes the whole frame to be discarded by the receiver, reducing frame size decreases the discarding of correctly received information for every bit error occurrence. The price we pay for that is that each frame transmission requires transmission of flags, control field, FCS etc. The use of smaller frame size makes the link perform well at high line BER.

To calculate optimum l values, the first derivative of D_b versus l is required. For small p_b,

$$p = 1-(1-p_b)^{l+l'} \approx 1-\left(1-(l+l')p_b\right) = (l+l')p_b \quad (18)$$

and by setting the first derivative equal to zero, after some valid approximations, we obtain

$$l_{opt} = \sqrt{\frac{2(Nl'+t_{ack}C)}{N^2 p_b}} \quad (19)$$

Fig. 6 also shows optimum frame size values versus BER for fixed window size N=127. It compares values obtained using (19) with optimum l values obtained using numerical methods on (14). As with window size N, a very good match is observed and all approximations are validated.

An important conclusion can be extracted by observing that (17) and (19) for optimum values can be rewritten as

$$Nlp_b \frac{Nl}{2} = t_{ack}C + Nl' \quad (20)$$

Equation (20) reveals that maximum throughput is achieved when the probability of a bit error in the optimum window frame transmission ($\approx Nlp_b$), times the number of bits that have to be retransmitted due to the error occurred, which on average is half the transmission window $Nl/2$, is equal to the acknowledgement time in bits $t_{ack}C$ plus the number of overhead bits in the window Nl'. The term Nl' is missing from (17) because, if optimum window size values are implemented, optimum N becomes relatively small for high BERs, so term Nl' can be safely neglected.

C. Simultaneously Optimum Window and Frame Size

If window and frame size link parameters can be simultaneously adjusted, maximum possible throughput performance can be achieved. For high BER, window size parameter N can be tuned to reduce the error probability in a window transmission and avoid the retransmission of correctly received out of sequence frames. Frame size parameter l can be tuned to balance between the increase of the frame error probability p and the overhead transmission l' involved in every frame transmission. To derive simultaneously optimum N and l values, throughput derivative versus N can be taken and set to zero following the analysis in section A. Optimum N values derived can be substituted to throughput equation. Throughput D_b becomes a function of frame size l for optimum N values. The derivative versus l can now be taken and set equal to zero to derive optimum l values. N_{opt} given by (16) should be used as the assumption $l>>l'$ is no longer valid as optimum l values may be significantly small. Taking the approximation $p \approx (l+l')p_b$, (16) can be rewritten as

$$N_{opt}(l+l') = \sqrt{\frac{2t_{ack}C}{p_b}} = \text{constant} \quad (21)$$

Throughput D_b can be rewritten as

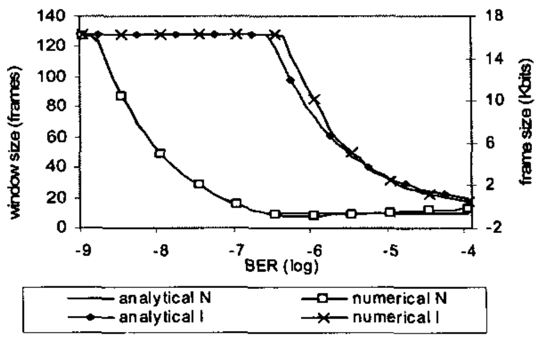


Fig. 7. Optimum widow and frame size comparison, C=16Mbit/s, t_{ta}=0.1ms

$$D_b = \frac{l(1-p_b)^{l+l'}}{\left(1-(1-p_b)^{l+l'}\right)} \frac{\left(1-(1-p_b)^{N(l+l')}\right)}{\left(N(l+l')/C + p(t_{Fout}+t_s) + t_{ack}\right)} \quad (22)$$

Substituting (21) to (22), assuming the valid approximation $p \approx (l+l')p_b$ and setting the first derivative versus l equal to zero, after some approximations we derive

$$l_{opt} = \sqrt{\frac{l'}{p_b}} \quad (23)$$

By substituting (23) into (21), we obtain

$$N_{opt} \approx \sqrt{\frac{2t_{ack}C}{l'}} \quad (24)$$

Fig. 7 plots simultaneous optimum window and frame sizes for links with t_{ta}=0.1ms and C=16Mbit/s. It is observed that for a range of BERs (less than $10^{-6.5}$), (23) suggests that frame size values greater than the maximum allowed value of 16Kbits should be employed. For this range, optimum N values are given by (17) instead of (24) since optimum frame size values are constant for this range. Since a very good match is observed between approximated optimum values given by (17), (23), (24) and optimum values derived by using numerical methods, approximations made in (14) to derive (23) and (24) are validated. Slight differences are observed resulting in negligible difference in throughput efficiency as shown in Fig. 8.

An important conclusion can be extracted by observing that (17) and (23) for optimum values can be rewritten as

$$N_{opt} l_{opt} p_b \frac{N_{opt} l_{opt}}{2} = t_{ack}C \quad (25)$$

$$l_{opt}\, p_b\, l_{opt} = l' \quad (26)$$

Equation (26) reveals that optimum throughput is achieved when the probability of a bit error in the optimum frame ($\approx l_{opt}p_b$), times the number of frame bits that have to be retransmitted due to this error ($=l_{opt}$) must be equal to the frame bit overhead l'. This equation shows that optimum frame size values should balance between time spent on retransmitting error frames and time spent on transmitting overheads. Equation (25) shows that maximum throughput is achieved when the probability of a bit error in the optimum window frame

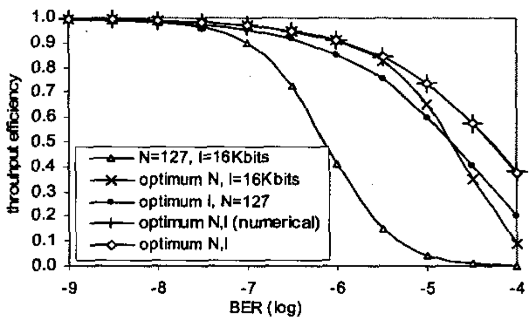


Fig. 8. Throughput against BER for 16Mbit/s link, t_{ta}=0.1ms

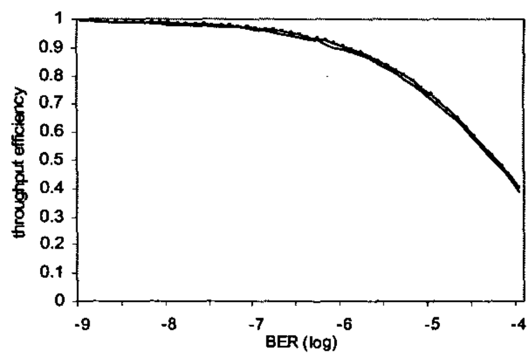
transmission ($\approx N_{opt} l_{opt} p_b$), times the number of bits that have to be retransmitted in the following frames due to the error occurred, which on average is half the window transmission $N_{opt} l_{opt}/2$, is equal to the acknowledgement time in bits $t_{ack}C$. In other words, the time for the bits transmitted in a window transmission, $N_{opt} l_{opt}$, should balance between time utilized in retransmitting out of sequence frames and time utilized on acknowledgements.

VII Throughput Analysis Using Optimum Link Values

Fig. 8 compares throughput efficiency of a 16Mbit/s link with t_{ta}=0.1ms employing N=127 and l=16384 with the efficiency achieved by implementing optimum window size or frame size values given by (17) and (19) respectively. Throughput performance for optimum N values is higher than throughput performance for optimum l values for BERs lower that 10^{-5} because as window size is decreased, fewer frame overheads l' are transmitted. Fig. 8 shows that applying optimum window and frame size values simultaneously always gives better performance.

VIII Optimum Window and Frame Size Implementation

The practical usefulness of the derived optimum values for window and frame size is examined by means of simulation. The IrLAP OPNET simulator presented in section IV is modified to allow the transmitter to implement optimum window and frame size values simultaneously. The transmitter estimates link BER based on the number of frame retransmissions requested by the receiver. A very simple BER estimation algorithm is developed that allows the transmitter to efficiently estimate link BER based on the amount of successfully received information between two consecutive bit errors. Fig. 9 compares maximum throughput with simulated throughput efficiency when the transmitter implements only eleven different pairs of optimum values for window and frame size. Simulations run for 100 sec after a 'warm-up' period of 1 sec. Fig. 9 reveals that simulation throughput is almost identical to maximum throughput. Detailed implementation issues can also be found in [11]. As a conclusion, it is possible to achieve maximum throughput efficiency by adopting N and l according to the link BER.



■ maximum throughput (numerical) — simulation throughput

Fig. 9. Throughput comparison for implementing 11 pairs of window and frame size values, C=16 Mbit/s, t_{ta}=0.1 ms.

IX. Conclusions

An accurate mathematical analysis is presented for calculating the IrDA IrLAP throughput performance. The analysis leads to a simple equation for IrLAP throughput, which gives us insights on performance limitations and of the delays incorporated. The expressions relate throughput and delays with physical and link layer parameters such as link BER, link data rate, minimum turn around time, frame size and window size. Results are presented which identify the significance of different link parameters to throughput performance. The significance of minimum turn around time delay is revealed and explored for different IrDA links. We derived optimum window and/or frame size values that achieve maximum link layer throughput. The derived simple equations and optimum link layer values should be very useful to IrDA link layer designers in determining the effectiveness of physical and link layer parameters for maximum throughput.

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