100Mb/s IrDA Protocol Performance Evaluation

A. C. Boucouvalas and V. Vitsas*
Multimedia Communications Research Group,
School of Design, Engineering and Computing,
Bournemouth University, Fern Barrow, Poole, Dorset, BH12 5BB, UK
{tboucouv,vvitsas@bournemouth.ac.uk}

Abstract—**IrDA optical wireless links operate at data rate up to 4Mb/s with the possibility of extending the data rate to 16 Mb/s in the near future. Longer term, IrDA is destined to creating standards for links at even higher data rates. The purpose of this work is to examine the IrDA IrLAP protocol performance at data rates up to 100Mb/s.**

Using a mathematical analysis based on the concept of "window transmission time", the throughput equation of IrLAP is derived. Subsequently optimum values for important design parameters of the link layer such as window size and frame length are derived, for maximum IrLAP throughput as a function of BER. Our results indicate that the IrLAP protocol offers excellent performance even at 100Mb/s, with high Link layer throughput even at high data error rates, provided IrLAP window size and frame length values are adapted to the corresponding optimum values for the BER. Results are presented on the link performance limitation due to the turnaround time.

I. INTRODUCTION

Numerous IrDA based consumer electronic and computer products are available including mobile telephones, PCs, printers, personal digital assistants, watches and cameras. Such products utilise low cost high speed IrDA short range optical wireless links, [1]. Market predictions expect a growth in IrDA enabled products from 300 million to 1.3 billion by year 2003. The predicted CAGR is 70% for mobile telephones, 52% for PDAs, 25% for PCs, 20% for printers and 16% for other products for the period 1999-2003. IrDA type optical wireless links have therefore become a major industry, used for tetherless interconnection between such devices. The majority of the links to-date offer data rates up to 4 Mb/s. Recently there has been a standardisation of the 16Mb/s data rate option, called *Very Fast Infrared,* (*VFIr*) [7]. IrDA products comply to the well known "point and shoot" usage model, with line of sight data transfers within short range (1m) making use of narrow optical beam (30^0).

VFIr links at 16 Mb/s will enable Ethernet rate connections and fast image transfer between devices for the next few years. It is therefore expected that eventually there will be demand for even higher data rate links than those offered by VFIr. The future will eventually bring to fore links of 40 Mb/s or even 100 Mb/s data rates for high-end applications. This article assumes that the existing IrLAP [2] protocol will be used for future higher speed links and examines how well the existing IrDA IrLAP protocol fares to predicted future increases of data rates. It offers guidelines for designers of such futuristic IrDA links on window size, frame length and turnaround time as a function of BER.

A simple equation is derived describing the IrLAP throughput as a function of probability of bit error, window size, frame length, turnaround time and other link layer parameters. Such equation is important to IrDA link designers. In order to design robust IrDA links under varying BER, (expected in wireless links), link designers require guidelines on how to optimise the IrLAP layer for maximum throughput. It is shown that dynamic adaptation of the window size and frame length allows for maximum IrLAP throughput, [3]. Equations are presented for optimum parameters for maximum throughput.

II. IRLAP PROTOCOL DESCRIPTION AND PARAMETER DEFINITIONS

IrLAP facilitates the interconnection of devices using a directed half duplex serial infrared link as defined in IrDA physical layer [4]. One device assumes primary and the other secondary role during link establishment. More than one device may assume the role of a secondary but only one can be primary. The primary controls the flow of information and all traffic flows via the primary station. The present work is limited to the interconnection of two devices, a primary and a secondary node.

IrLAP packets consist of an 8-bit address field, a 16-bit control field for 4Mb/s and 16Mb/s links and a variable length information field [7]. 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. S-frames do not 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. The control field, depending on frame type, may contain a send sequence number, Ns, used to number the frames sent. It may also contain a receive sequence number,

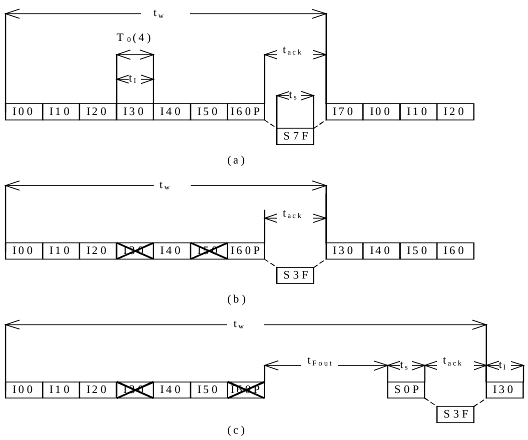

Figure 1: *(a) Error free transmission of a window (b) Retransmitted frames due to error frame at w = 4 (c) Retransmitted frames and F-timer delay due frame error at w = 4 and w =7.*

Nr, used to number frames correctly received.Valid Ns and Nr values are 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 the previous poll command.

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

Receive ready (RR) and reject (REJ) S-frame responses are only considered. The I-frame contains a send sequence number Ns, which circles through values 0 to 127 for 4Mb/s and 16Mb/s links. 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. S-frame REJ responses contain a receive sequence number Nr which rejects frame Nr and thus acknowledges the correct reception of frames up to Nr-1 and indicating that Nr is the next (retransmitted) frame expected.

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

$$t_S = \frac{l'}{C}, \qquad t_I = \frac{l+l'}{C}, \qquad t_{ack} = 2t_{ta} + t_S,$$

$$p = 1-(1-p_b)^{l+l'} \quad \text{and} \quad D_b = lD_f \qquad (1)$$

The window size N is the maximum number of unacknowledged frames that the transmitter can transmit. Its maximum value is 127. 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:

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_{Imax}	Transmission time of a 16Kbits 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

$$N = min\left\{W_{\max},\ floor\left(\frac{T_{\max}}{t_I}\right)\right\} \qquad (2)$$

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

Since the transmitter always has data packets ready for transmission, 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 expected data frame or the frame received is in error, respectively. The transmitter then determines the number of consecutive frames successfully received prior to any occurred error(s) and sends a new window with frame contents starting from the erred frame with the subsequent indexed frames following it. The window will be therefore be filled with retransmitted and 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, since the P bit is lost. The transmitter waits 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.

(1) The concept of the “window transmission time” (WTT) is used to denote 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 in this particular window received in error, WTT t_w, is given by

$$t_w = Nt_I + t_{ack} \tag{3}$$

If the last frame in 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). This situation incorporates an additional delay of $t_{Fout} + t_s$ and WTT is given by

$$t_w = Nt_I + t_{Fout} + t_s + t_{ack} \tag{4}$$

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

$$t_w = Nt_I + p\left(t_{Fout} + t_s\right) + t_{ack} \tag{5}$$

Since 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

$$p_c(w) = (1-p)^w p\,,\ w=1,2,\ldots,N-1 \tag{6}$$

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

$$p_c(N) = (1-p)^N \tag{7}$$

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

$$p_{all} = \sum_{w=1}^{N} w p_c(w),\ w=1,2,\ldots,N \tag{8}$$

The frame troughtput 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 $t_{w,}$ hence using (1) and after some algebra we derive:

$$\boxed{D_b = l\,\frac{1-p}{p}\,\frac{\left(1-(1-p)^N\right)}{Nt_I + p\left(t_{Fout}+t_s\right) + t_{ack}}} \tag{9}$$

The relative time consumed in each of the protocol tasks affecting IrLAP performance is given next.

The time portion taken on frame acknowledgements is T_{tack} and the time portion on P bit loss are given by

$$T_{tack} = \frac{t_{ack}}{Nt_I + p\left(t_{Fout}+t_s\right) + t_{ack}} \tag{10}$$

$$T_{Fout} = \frac{p\left(t_{Fout}+t_s\right)}{Nt_I + p\left(t_{Fout}+t_s\right) + t_{ack}} \tag{11}$$

respectively.

Time portion of the overall time, which is consumed on transmitting frame overheads l' is given by $T_{l'}$. The expected number of error frames in a window transmission is Np, hence the time portion spent on retransmission of erred frames is T_{error}, where:

$$T_{l'} = \frac{Nl'/C}{Nt_I + p\left(t_{Fout}+t_s\right) + t_{ack}} \tag{12}$$

$$T_{error} = \frac{Npl/C}{Nt_I + p\left(t_{Fout}+t_s\right) + t_{ack}} \tag{13}$$

The expected number of correctly transmitted frames following an error frame in a window transmission can be found from the total number of transmitted frames in a window N, if we subtract a) the error frames Np and b) the correct in sequence received frames $(1-p)(1-(1-p)^N)/p$. Thus the time portion spent on retransmitting out of sequence correctly received frames is given by:

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

IV. THROUGHPUT ANALYSIS

Equation (9) allows us to get an intuitive understanding of IrLAP performance. Three factors contribute to average WTT given in (5). Factor Nt_I stands for user data transmission, factor $p(t_{Fout}+t_s)$ stands for lost P/F bit overhead and t_{ack} stands for delays introduced by reversing link direction. It is clear that for very low BERs, factor $p(t_{Fout}+t_s)$ introduces negligible overhead as the P/F bit is seldom lost. Table II shows the evolution of the remaining two factors for different data rates over the years. Ir-PHY ver 1.0 Serial Infrared (SIR) specification [5] supported data rates up to 115.2 Kb/s using standard serial hardware, Ir-PHY ver 1.1 Fast Infrared (FIR) [6] extended data speed to 4Mb/s and finally Ir-PHY ver 1.3 Very Fast Infrared (VFIR) [7] specification added the 16Mb/s link rate. Table II presents the data rates introduced by successive specifications, the maximum window size defined by the specification, maximum window size that can be enforced for 16Kbit frames within T_{max} (N), the t_{ta} and the two further factors, t_{ack} and Nt_I, that contribute to WTT. Table II reveals that although FIR introduced much higher speeds (up to 4Mb/s), it did not change the maximum t_{ta} value allowed for FIR IrDA ports. As a result, time spent for useful data transmission dropped to 28.8 ms while time spent on reversing link direction twice, was 20 ms. For comparison in Table II the 100Mb/s data rate is also included with t_{ta}
and =0.1ms and t_{ta} =0.01ms.

Fig. 2 plots throughput efficiency versus BER for 100Mb/s link rate with t_{ta}=0.1ms, l=16Kbits and for W_{max}=127, W_{max}=67, and W_{max}=7. For those values and low BER the efficiency is improving with larger window size. The situation is reversed for higher BER values, where the throughput is better for window size 7 than 127. The throughput efficiency can be as high as 0.98 for low BER and W_{max}=127 but only 0.84 for W_{max}=7. Clearly the choice of W_{max} is critical in order to achieve optimum performance for any BER. In [8] we have shown that improvement in throughput performance is also possible by adapting the frame length as well. IrLAP window and frame size simultaneous adaptivity has not been examined previously.

The two questions dealt in this work are:

A) How do we achieve optimum performance for any BER by adjusting the window size and frame length and
B) What should the minimum turnaround time be for data rates up to 100Mb/s IrLAP.

TABLE II

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

specification	speed	year	W_{max}	N	Nt_I (ms)	t_{ta} (ms)	t_{ack} (ms)
SIR	115.2 Kb/s	1994	7	3	427.9	10	20.00
FIR	576 Kb/s	1995	7	7	199.7	10	20.0
FIR	1.152 Mb/s	1995	7	7	99.8	10	20.0
FIR	4 Mb/s	1995	7	7	28.8	10	20.0
VFIR	4 Mb/s	1999	127	121	497.8	10	20.0
VFIR	16 Mb/s	1999	127	127	130.6	0.1	0.20
	100 Mb/s		127	127	20.9	0.1	0.20
	100 Mb/s		127	127	20.9	0.01	0.02

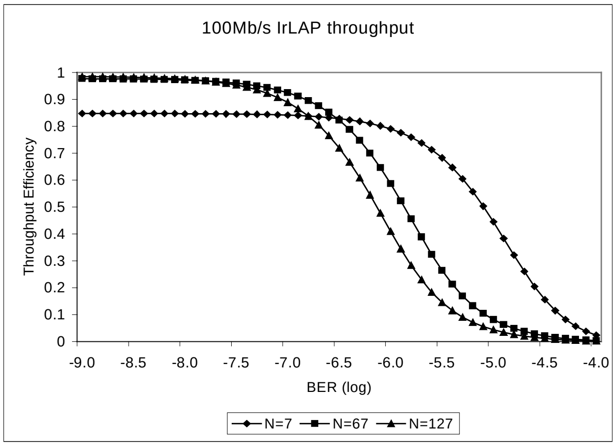

Figure 2. *Throughput Efficiency versus BER for 100Mb/s for t_{ta}=0.1ms, l=16Kbits*

V. OPTIMUM LINK PARAMETER VALUES

Equation (9) is a function of both window size *N* and frame length *l*. It has been shown that the throughput, (9), may be optimised by varying those variables. It is of interest therefore to derive the optimum values of *N* and *l*, that maximise D_b. There are two strategies of interest to us in maximising the throughput D_b. The first approach is twofold:

a) Deriving N_{opt} for maximum D_b for fixed *l*. $\frac{\partial D_b}{\partial N}=0$ allows us to calculate N_{opt} for maximum D_b for any given BER. This allows link designers having fixed frame length *l* hardware, to adjust only *N* to a calculated N_{opt} for any specific values of BER and *l* and obtain a local maximum throughput for the chosen parameters.

b) Deriving l_{opt} for maximum D_b for fixed *N*. $\frac{\partial D_b}{\partial l}=0$ allows us to calculate l_{opt} for maximum D_b for any given BER. The approach here is to adjust *l* alone keeping the window size *N* fixed. Here *l* is adjusted to l_{opt} for any fixed BER and *N* values. This will produce a maximum IrLAP throughput for the local parameters chosen.

The second approach is an extension of the above and offers the best possible IrLAP throughput, D_b, for any BER. It is based on deriving the maximum of D_b for both *l* and *N* simultaneously. In order to achieve this, both *l* and *N* vary simultaneously to a calculated N_{opt} and l_{opt} as a function of BER. N_{opt} and l_{opt} are both derived by solving $\frac{\partial D_b}{\partial N}=\frac{\partial D_b}{\partial l}=0$.

The value for t_{Fout} implemented in the current work is $t_{Fout}=t_{\mathrm{Im}ax}+2t_{ta}$. This corresponds to a maximum window size parameter of value equal to one for secondary station negotiated and agreed during link establishment.

Approach A: Optimum Window or Frame Size for maximum throughput

In order to derive the optimum values for different link parameters, (9) is differentiated and set to zero.

By taking $\frac{\partial D_b}{\partial N}=0$ we derive in [8], to a good approximation N_{opt} for any fixed *l* value.

Also, for fixed *N*, optimum *l* values are derived, by taking the derivative of D_b versus *l* and setting it to zero, $\frac{\partial D_b}{\partial l}=0$. After some calculus, [8], good approximations are derived for N_{opt} and l_{opt}.

$$\boxed{N_{opt}=\sqrt{\frac{2t_{ack}C}{l^2 p_b}}} \quad (15) \qquad \boxed{l_{opt}=\sqrt{\frac{2(Nl'+t_{ack}C)}{N^2 p_b}}} \quad (16)$$

Approach B: Optimum Window and Frame Size for maximum throughput.

Assuming that both window and frame size link parameters can be simultaneously adjusted, the 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 optimum *N* and *l* values, throughput derivative versus *N* can be taken and set to zero following the analysis in Approach 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 l_{opt} values, essentially deriving the conditions for $\frac{\partial D_b}{\partial N} = \frac{\partial D_b}{\partial l}$ =0. It can be shown that in this case, l_{opt} and N_{opt} are given approximately by:

$$\boxed{l_{opt} = \sqrt{\frac{l'}{p_b}}} \quad (17) \quad \text{and} \quad \boxed{N_{opt} \approx \sqrt{\frac{2t_{ack}C}{l'}}} \quad (18)$$

In this case, (18) reveals N_{opt} is small and independent of BER, (approximately). l_{opt} should be very large and takes values larger than 16Kbits (for low error rates $<2.6X10^{-7}$), a value not allowed by IrDA specification. In practice therefore one is restricted to using both approaches for optimum IrDA IrLAP results. We use approach A, eqn(15), for low error rates, where reducing *N* is the best strategy for fixed *l*=16Kbits, until the calculated l_{opt} is less than 16Kbits (~ BER= $2.6X10^{-7}$ from (17) using l'=72, and l_{opt} =16384 bits). Thereafter for higher BER approach B is implemented (equations (17) and (18)), for N_{opt} and l_{opt}) yields optimum IrLAP throughput results.

VI MINIMUM TURNAROUND TIME FOR 100Mb/s IrLAP PROTOCOL

For high data rate, high performance and robust to BER degradation IrDA links, the IrLAP layer parameters must be optimised. For IrDA short distance links, the minimum turnaround time parameter is very important. In this section IrLAP throughput efficiency is examined by varying the turnaround time for data rates of 4Mb/s, 16Mb/s 40Mb/s and 100Mb/s. The results below are for non-optimum IrLAP *N* and *l* parameters with *N*=127 and 7, *l*=16384 bits for extreme BER values of 10^{-9} and 10^{-6}.

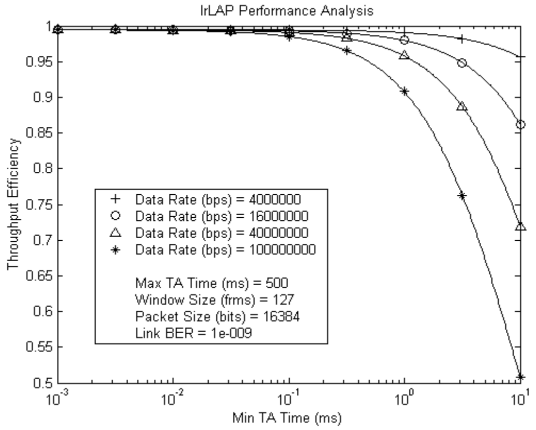

Figure 3*: Effect of min. turnaround time of throughput, for N=127, BER=10^{-9}*

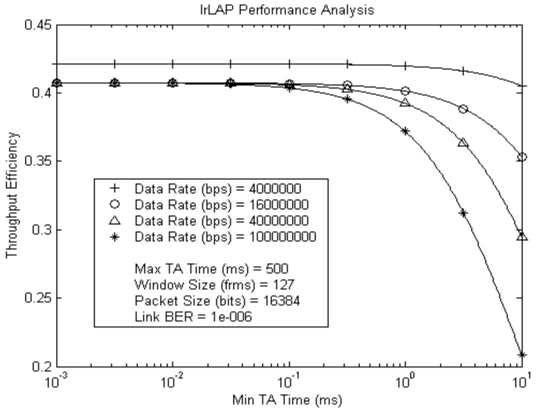

Figure 4: *Min. turnaround time of throughput for N=127, BER=10^{-6}*

For *N*=127, *l*=16384 bits and BER < 10^{-6} (Fig. 3-4), the figures reveal that the turnaround time has additional detrimental effect only when it becomes >0.1ms for all the data rates we consider here. It appears that it is not the main factor contributing to the decrease in throughput provided t_{ta} <0.1ms. For *N*=7, *l*=16384 bits and BER < 10^{-6} (Fig. 5-6), the turnaround time should be t_{ta} <0.01ms. Clearly for the BER range considered here, the fact that fixed window size *N* and frame length *l* (non-optimal) are used has more significant impact on throughput deterioration than turnaround time has, provided t_{ta} <0.01ms. For non optimum values of *N* and *l*, therefore the minimum turnaround time could be as high as 0.01 ms for *N*=7. In the next section we examine the minimum turnaround time desired when optimum values of *N* and *l* are used, when the required link throughput is high even in situations when the link experiences high BER.

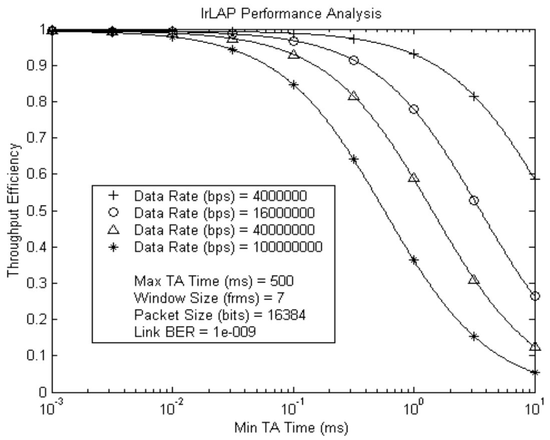

Figure5: *Min. turnaround time on throughput for N=7 BER=10^{-9}*

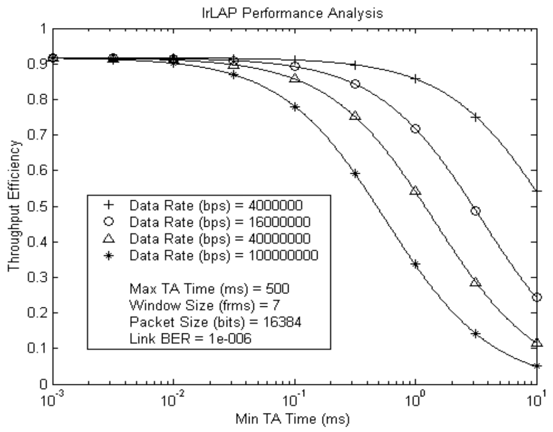

Figure 6: Min. turnaround time on throughput for N=7 BER=10^{-6}

VII MINIMUM TURNAROUND TIME USING OPTIMUM LINK VALUES

In order to examine the effect of minimum turnaround time on links up to 100Mb/s data rate, and for links robust to high BER, optimum values for *l* for low *N* values are considered. Figures 7-10, show the IrLAP throughput efficiency versus *l*, for the worst error rate considered here, BER=10^{-4}. The value of BER chosen here is arbitrary high, but high enough for robust links. For lower BER the links operating with the recommended t_{ta} will of course function even better. We have chosen *N*=7 because we have shown that for high error rates *N* should be small. Varying *l* we can identify the optimum *l* for N=7, for maximum throughput. The effect of t_{ta} has on maximum throughput can be determined by varying the t_{ta} parameter from 0.1 to 0.0001ms.

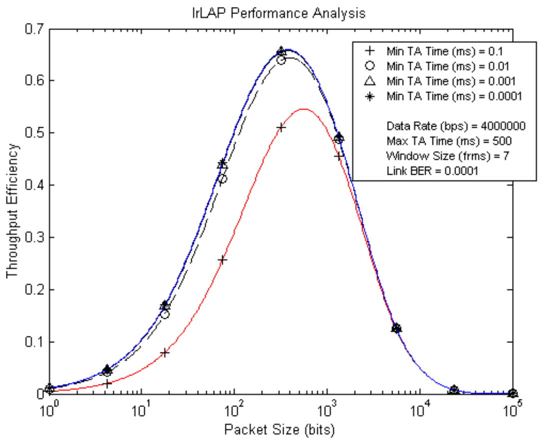

Figure 7: *Mn. turnaround time on throughput N=7 BER=10^{-4}, 4Mb/s*

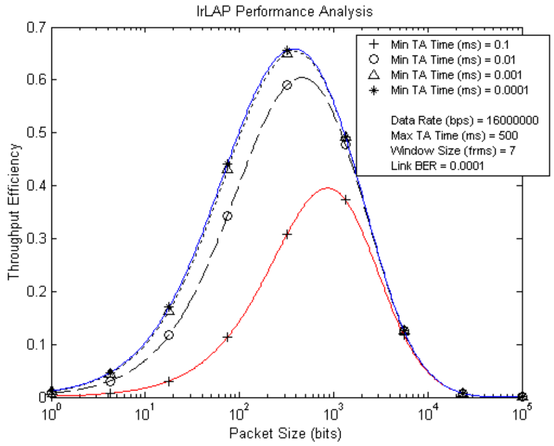

Figure 8: *Min. turnaround time on throughput N=7 BER=10^{-4}, 16Mb/s*

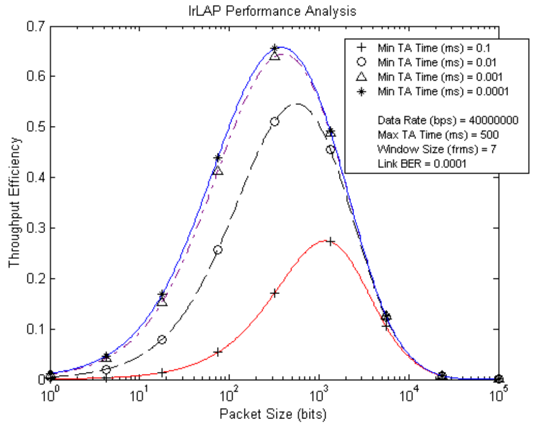

Figure 9: *Min. turnaround time on throughput N=7, BER=10^{-4}, 40Mb/s*

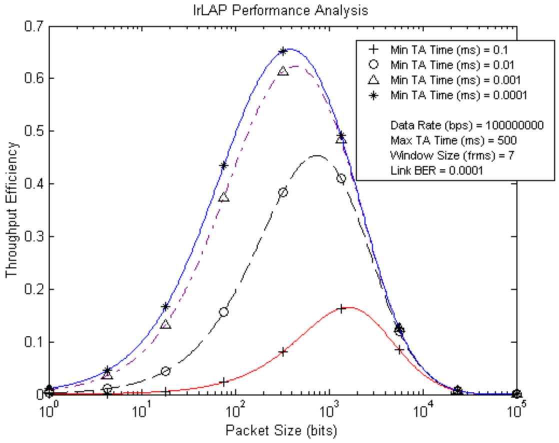

Figure 10: *Min. turnaround time on throughput N=7, BER=10^{-4}, 100Mb/s*

The link data rates here are chosen to be 4, 16, 40, and 100Mb/s respectively reflecting existing and possible future data rates for IrDA links. It is clear that for 4Mb/s and for optimum *l*, the link would benefit with t_{ta}=0.01ms (an order of magnitude lower than the value the IrDA standard specifies), provided an adaptive Link layer with variable *N* and *l* is adopted as per Approach B in this paper.

Similarly, for 16Mb/s links t_{ta}=0.01ms would double throughput at high error rates when simultaneously optimum values of *N* and *l* are used when compared to the maximum throughput possible with the existing values of the IrDA standard. For future links, say 40Mb/s, from Figure 9 we can deduce that a t_{ta} value between 0.01 and 0.001ms would be desired. Finally, for 100Mb/s links, as shown in Figure 10, a t_{ta} of 0.001 ms (10^{-6} s) is necessary for similar throughput efficiency values. Reducing t_{ta} to less than 10^{-6} s does not improve the throughput significantly for data rates of 100Mbit/s.

VIII EFFECT OF MINIMUM TURNAROUND TIME ON THROUGHPUT OF 100Mb/s LINKS USING OPTIMUM LINK *N* AND *l* VALUES.

In this section the IrLAP throughput efficiency of 100Mb/s links using optimum *N* and *l* values are compared in Figures 11-18, using t_{ta} as a parameter, varying from 0.1ms to 0.0001ms. The figures are being displayed in pairs. The figures on the right show the optimum values *N* and *l* used versus BER in producing the corresponding figure on the left. The throughput figures are shown in decreasing values of t_{ta} in order to examine the effect of turnaround time on throughput efficiency. Figures 11,13,15, and 17 also show the efficiency loss, (time wasted for other tasks of the protocol, than useful data transfer, based on equations 10,11,12,13, and 14). Such efficiency wasting tasks increase their influence on affecting negatively throughput with increasing BER for all the figures shown below. It can be seen in Figure 11 that a t_{ta} =0.1ms which contributes significantly into t_{ack}, produces the most significant component of efficiency detriment for high BER.

Reducing t_{ta} to 0.01ms in Figure 13, significantly reduces the t_{ack} component and as a result increases the overall throughput efficiency to approximately 0.4 for BER =10^{-4}. Further reduction of t_{ta} to 0.001ms, (Fig.15), improves the throughput efficiency to approximately 0.6 for BER =10^{-4} (confirming the result of Figure 10) and eliminates the significance of $t_{ack.}$ Finally efficiency detriment due to t_{Fout} becomes significant and resistant to t_{ta} even for t_{ta} = 0.0001ms, (Fig.17). Therefore, in order to improve further the throughput efficiency subsequent to reducing for t_{ta}, a reduction in t_{Fout} is the one that would have a positive effect. From Figure 17, we deduce that reducing t_{ta} from 1 to 0.1μs does not improve throughput significantly and it is not therefore necessary.

It has been shown therefore that for 100Mb/s links, the turnaround time if reduced to as low as 1μs, in combination with use of simultaneously optimal *N* and *l* values, (eqns 15,17,18), offers a high throughput efficiency approaching 0.6, even at BER as high as 10^{-4}.

IX. CONCLUSIONS

The performance of IrDA IrLAP protocol operating at data rate of 100Mbit/s has been examined. Such a high data rate maybe considered for future generations of IrDA optical wireless point to point links. It has been shown that the protocol offers high throughput efficiency even at high bit error rates when presented with simultaneously optimal values for *N* and *l*. The performance results indicate that a turnaround time of less than 1μs, would yield excellent throughput results. The optimal values for *N* and *l* are in accordance to simple equations, which are derived from first principles. By adjusting the window and frame lengths we ensure high throughput at the Link layer even at high BER.

We conclude that the IrLAP protocol is not a limitation for increasing the IrDA data rates to 100Mbit/s. This is possible provided that PHY layer hardware of appropriate turnaround time and BER at the required data rate can be made. Adaptive change of *N* and *l*, yields optimum high Link layer throughput over wide BER.

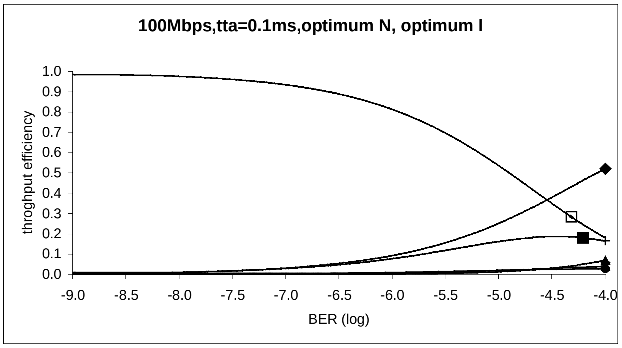

Figure 11:

- □ *useful data transmission (throughput efficiency)*
- ■ *retransmission of correctly received out of sequence frames*
- ✗ *retransmission of error frames*
- ◆ *t_{ack} time of frames*
- ● *reversing link direction (hardware latency)*

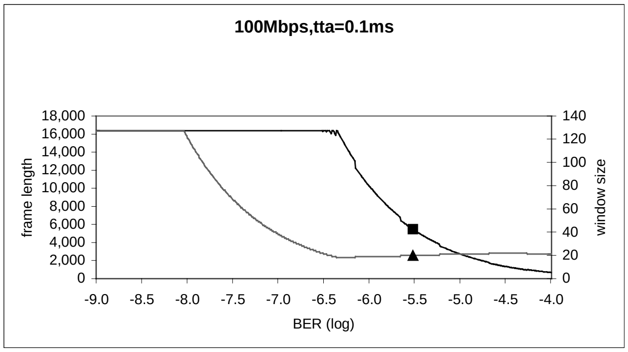

Figure 12:

■ *Optimum frame length,* ▲ *Optimum window size for Figure 11*

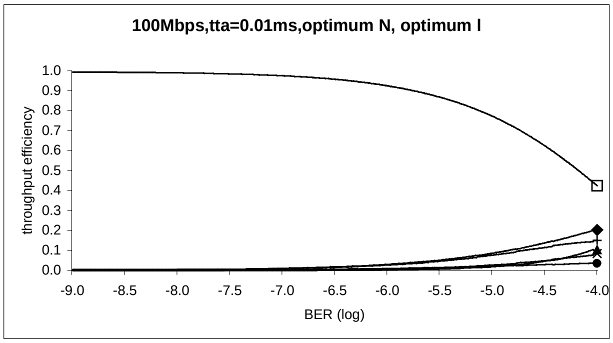

Figure 13

- □ *useful data transmission (throughput efficiency)*
- + *retransmission of correctly received out of sequence frames*
- ▲ *t_{Fout} timer expiration*
- ◆ *t_{ack} time of frames*
- ● *retransmission of error frames*

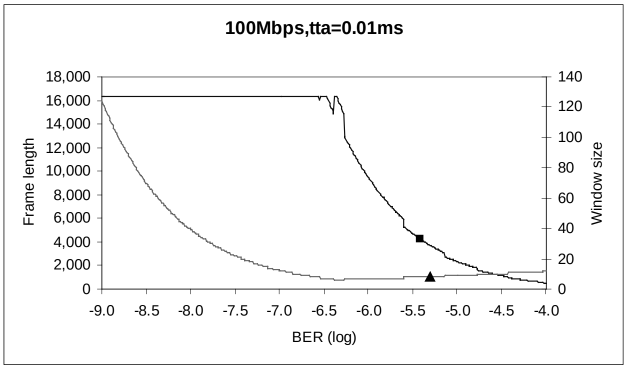

Figure 14

■ *Optimum frame length*, ▲ *Optimum window size for Figure 13*

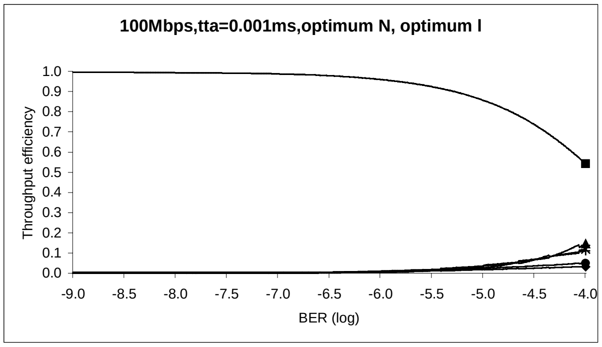

Figure 15:

- ■ *useful data transmission (throughput efficiency)*
- + *retransmission of correctly received out of sequence frames*
- ● *retransmission of error frames*
- ▲ *t_{Fout} timer expiration*

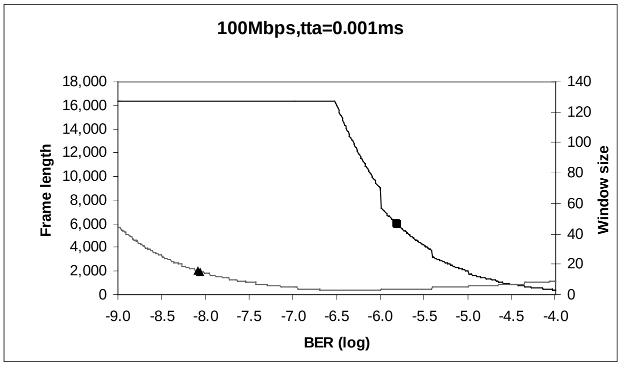

Figure 16:

■ *Optimum frame length*, ▲ *Optimum window size for Figure 15*

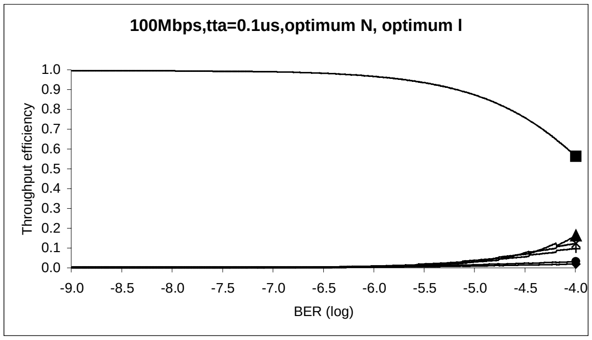

Figure 17

■ *useful data transmission (throughput efficiency)*
+ *retransmission of correctly received out of sequence frames*
● *retransmission of error frames*
▲ t_{Fout} *timer expiration*

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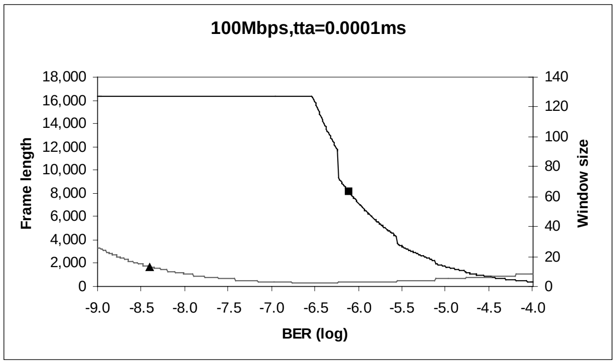

Figure 18

■ *Optimum frame length,* ▲ *Optimum window size for Figure 17*