100 Mbit/s IrDA optical wireless throughput performance analysis

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Abstract: Existing IrDA standard optical wireless links operate at data rates up to 16 Mbit/s. Such links are incorporated into millions of products such as mobile phones, personal digital assistants, laptop and palmtop PCs. Longer term, IrDA is destined to create standards for links at even higher data rates. The performance of such links depends crucially on the efficient operation of the IrDA IrLAP protocol. The authors examine the IrDA IrLAP protocol performance at data rates up to 100 Mbit/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. The results indicate that the IrLAP protocol offers excellent performance even at 100 Mbit/s. High link layer throughput even at high data bit error rates is possible provided the IrLAP window size and frame length values are adapted to optimum values for the corresponding BER. Results are presented on link performance limited due to the turnaround time. Such results are important to hardware manufacturers of high speed optical wireless links.

1 Introduction

Numerous IrDA based consumer electronic and computer products are available including mobile telephones, PCs, printers, personal digital assistants (PDAs), watches and cameras. Such products utilise low cost high speed IrDA short range optical wireless links [1–4]. 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 Mbit/s. Recently there has been a standardisation of the 16 Mbit/s data rate option, called 'very fast infrared' (*VFIr*) [5]. IrDA products comply to the well known 'point and shoot' usage model, with line-of-sight data transfers within short range (1 m) making use of narrow optical beam (30°).

VFIr links at 16 Mbit/s 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 the fore links of 40 Mbit/s or even 100 Mbit/s data rates for high-end applications. Recent IrDA specifications [6] for the transmission of multimedia objects (such as video (MPEG4), pictures (JPEG) and music (MP3)) suggest the future development of the 100 Mbit/s data rate and the implementation of high window sizes at the IrLAP layer and of small minimum turn around times at the physical layer. This article assumes that the existing IrDA data link layer IrLAP [7] 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. The results offer guidelines for designers of such futuristic IrDA links on the choice of window size, frame length and turnaround time as a function of link BER.

IrLAP is a derivative of widely used HDLC protocol and utilises a go-back-N (GBN) automatic repeat request (ARQ) scheme to ensure reliable information transfer [7]. Performance of GBN ARQ schemes is presented in [8, 9]. The HDLC throughput performance model [10] can be simplified for IrLAP by taking advantage of the half-duplex operation of the IrLAP protocol [11]. A simple equation is derived describing the IrLAP throughput as a function of bit error probability, window size, frame length, turnaround time and other link layer parameters. Such an 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 [12]. Equations are presented for optimum parameters for maximum throughput.

2 IrLAP protocol description and parameter definitions

IrLAP facilitates the interconnection of devices using a directed half duplex serial infrared link as defined in the IrDA physical layer [13]. 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 the 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.

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IrLAP packets consist of an 8-bit address field, a 16-bit control field for 4 Mbit/s and 16 Mbit/s links and a variable length information field [5]. The control field contains an identifier, which determines the frame type. Unnumbered frames (U-frames), supervisory frames (S-frames) and information frames (I-frames) are supported. U-frames are used in establishing and disconnecting links and in reporting procedural errors. S-frames assist in the transfer of information, although they do not carry information data. S-frames are used to acknowledge correctly received frames, report frame sequencing errors and convey ready or busy conditions. I-frames carry information data across the link. The control field, depending on frame type, may contain a send sequence number, *N*s, used to number the frames sent. It may also contain a 'receive sequence number', *N*r, used to number frames correctly received. Valid *N*s and *N*r 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 the primary to the 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 secondary responses only are considered. The I-frame contains a send sequence number, *N*s, which circles through values 0 to 127 for 4 Mbit/s and 16 Mbit/s links. S-frame RR responses contain a receive sequence number *N*r which acknowledges the correct reception of frames up to $Nr - 1$, thus indicating that *N*r is the next frame expected. S-frame REJ responses contain a receive sequence number *N*r which rejects frame *N*r and thus acknowledges the correct reception of frames up to $Nr - 1$ and, therefore, indicates that *N*r is the next (retransmitted) frame expected.

The relevant parameters and symbols used in the analysis are shown in Table 1. Values for t_s, t_I, t_{ack}, p and D_b are given by

$$t_s = \frac{l'}{C}, \quad t_I = \frac{l + l'}{C}, \quad t_{ack} = 2t_{ta} + t_s,$$
$$p = 1 - (1 - p_b)^{l+l'} \quad \text{and} \quad D_b = lD_f \tag{1}$$

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 [7]. Thus, N is given by

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

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 error(s) occurred and sends a new window with frame contents starting from the first erred frame with the subsequent indexed frames following it. The window will 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 frame forcing the receiver to respond. RR and REJ frames are considered small enough to be error free.

Table 1: Parameters used in modelling IrLAP throughput

Symbol	Parameter description	Unit
C	Link data bit rate	bit/s
p_b	Link bit error rate	-
p	Frame error probability	-
l	I-frame message data length	bit
l'	S-frame length/I-frame overhead	bit
t_I	Transmission time of an I-frame	s
t_{Imax}	Transmission time of a 16 kbit I-frame	s
t_s	Transmission time of an S-frame	s
t_{ta}	Minimum turn-around time	s
t_{ack}	Acknowledgement time	s
T_{max}	Maximum turn-around time	s
t_{Fout}	F-timer time-out period	s
D_f	Frame throughput	frame/s
D_b	Data throughput	bit/s

3 Mathematical model of IrLAP protocol

The term 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 the next window's first frame transmission. WTT incorporates the time needed for frame transmissions and acknowledgements, delays for reversing the link and timer timeouts. As shown in Figs. 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

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

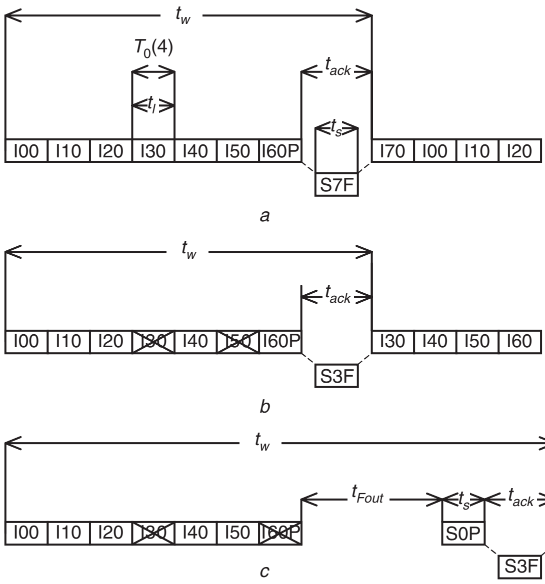

Fig. 1 *Window transmission*

a Error free transmission of a window
b Retransmitted frames due to error frame at $w = 4$ and $w = 6$
c Retransmitted frames and F-timer delay due frame error at $w = 4$ and $w = 7$

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

$$p_c(w) = (1 - p)^w p, \quad w = 0, 1, 2, \ldots, N - 1 \tag{6}$$

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

$$p_{all} = \sum_{w=0}^{N} w p_c(w) \tag{8}$$

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, hence using (1) and after some algebra we derive:

$$D_b = l \frac{1 - p}{p} \frac{(1 - (1 - p)^N)}{N t_I + p(t_{Fout} + t_s) + t_{ack}} \tag{9}$$

The relative time consumed in each of the protocol tasks affecting IrLAP performance is given next. The time portion taken on frame acknowledgements and the time portion on P bit loss are given by

$$T_{tack} = \frac{t_{ack}}{N t_I + p(t_{Fout} + t_s) + t_{ack}} \tag{10}$$

and

$$T_{Fout} = \frac{p(t_{Fout} + t_s)}{N t_I + p(t_{Fout} + t_s) + t_{ack}} \tag{11}$$

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:

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

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

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:

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

4 Throughput analysis

Equation (9) allows us to get an intuitive understanding of IrLAP performance. Three factors contribute to average WTT given in (5). Factor $N t_I$ 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 2 shows the evolution of the remaining two factors for different data rates over the years. Ir-PHY ver 1.0 Serial Infrared (SIR) specification [14] supported data rates up to 115.2 kbit/s using standard serial hardware, Ir-PHY ver 1.1 Fast Infrared (FIR) [15] extended data speed to 4 Mbit/s and finally Ir-PHY ver 1.3 Very Fast Infrared, (VFIR) [5] specification added the 16 Mbit/s link rate. Table 2 presents the data rates introduced by successive specifications, the maximum window size defined by the specification, maximum window size that can be enforced for 16 kbit frames within $T_{\max}(N)$, the t_{ta} and the two further factors, t_{ack} and $N t_I$, that contribute to WTT. Table 2 reveals that although FIR introduced much higher speeds (up to 4 Mbit/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 2 the 100 Mbit/s data rate is also included with $t_{ta} = 0.1$ ms and $t_{ta} = 0.01$ ms.

Figure 2 plots throughput efficiency against BER for 100 Mbit/s link rate with $t_{ta} = 0.1$ ms, $l = 16$ kbit/s and for $N = 127$, $N = 67$, and $N = 7$. 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 for window size 127. For low BER, the throughput efficiency can be as high as 0.98 for $N = 127$ but only 0.84 for $N = 7$. Clearly the choice of N is critical in order to achieve optimum performance for any BER. In [16] we have shown that improvement in throughput performance is also possible by adapting the frame length as well. Simulation results indicate that optimum window and frame size implementation practically achieves high throughput performance if the transmitter estimates link BER [17].

Table 2: Nt_l and t_{ack} for SIR and FIR data rates

Specification	Speed	Year	W_{max}	N	Nt_l (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
	100 Mbit/s		127	127	20.9	0.1	0.20
	100 Mbit/s		127	127	20.9	0.01	0.02

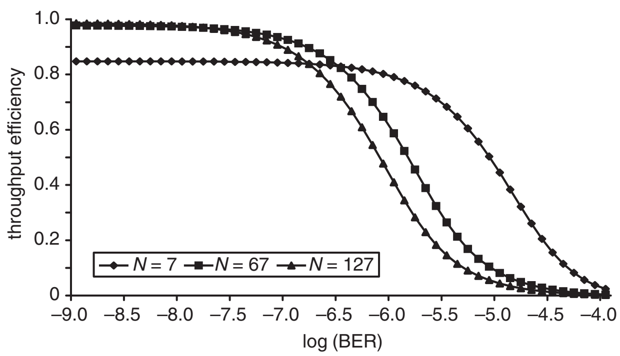

Fig. 2 *Throughput efficiency against BER at 100 Mbit/s for $t_{ta} = 0.1$ ms, $l = 16$ kbit/s*

The two questions addressed in this work are:

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

5 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, which 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. $\partial D_b/\partial N = 0$ 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. $\partial D_b/\partial l = 0$ 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 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 $\partial D_b/\partial N = \partial D_b/\partial l = 0$.

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

Approach 1: 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 $\partial D_b/\partial N = 0$ we derive in [16], 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, $\partial D_b/\partial l = 0$. After some calculus, [16], good approximations are derived for N_{opt} and l_{opt}.

$$N_{opt} = \sqrt{\frac{2t_{ack}C}{l^2 p_b}} \tag{15}$$

$$l_{opt} = \sqrt{\frac{2(Nl' + t_{ack}C)}{N^2 p_b}} \tag{16}$$

Approach 2: Simultaneous optimum window and frame size for maximum throughput
Assuming that both window and frame size link layer parameters can be adjusted simultaneously, 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 against N can be taken and set to zero following the analysis in approach 1. 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 $\partial D_b/\partial N = \partial D_b/\partial l = 0$. It can be shown that in this case, l_{opt} and N_{opt} are given approximately by:

$$l_{opt} = \sqrt{\frac{l'}{p_b}} \tag{17}$$

and

$$N_{opt} = \sqrt{\frac{2t_{ack}C}{l'}} \tag{18}$$

In this case, (18) reveals that N_{opt} is small and independent of BER (approximately). l_{opt} should be very large and takes values larger than 16 kbit/s (for low error rates $< 2.6 \times 10^{-7}$), 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 1, (15), for low error rates, where reducing N is the best strategy for fixed $l = 16$ kbit/s, until the calculated l_{opt} is less than 16 kbit/s ($\sim$BER $= 2.6 \times 10^{-7}$ from (17) using $l' = 72$ and $l_{opt} = 16384$ bits). Thereafter, for higher BER, approach 2 is implemented ((17) and (18)), for N_{opt} and l_{opt}, which yields optimum IrLAP throughput results.

6 Minimum turnaround time of high data rate IrLAP links using non-optimum *N* and *l* values

In order to achieve high performance and robust to BER degradation IrDA links, the IrLAP layer parameters l and N must be adapted dynamically as described in the previous Section. The minimum turnaround time parameter determines the time required by the circuits to reverse from transmitting to receiving. It is a very important hardware parameter affecting IrLAP performance. Although it is understood that the minimum turnaround time should be minimised, there are no guidelines available on how low the minimum turnaround time should be at various data rates. Similarly when the BER of the wireless link varies, the links should perform robustly for a good range of BER. In this Section IrLAP throughput efficiency is examined by varying the turnaround time for data rates of 4 Mbit/s, 16 Mbit/s 40 Mbit/s and 100 Mbit/s. We first plot throughput results for non-optimum N and l parameters, using $N = 127$ and 7, for $l = 16384$ bits and for extreme BER values of 10^{-9} and 10^{-6}, as shown in Figs. 3–6, respectively.

For $N = 127$, $l = 16384$ bits and BER $< 10^{-6}$ (Figs. 3 and 4), the figures reveal that the turnaround time has significant detrimental effect on throughput only when it becomes > 0.1 ms for all data rates considered. It appears that for $t_{ta} < 0.1$ ms (Fig. 4), factors other than t_{ta} have caused the decrease in throughput to $\sim$0.41. For smaller windows, $N = 7$, for $l = 16384$ bits and BER $< 10^{-6}$ (Figs. 5 and 6), the turnaround time should be smaller, $t_{ta} < 0.01$ ms, because the link turnaround frequency has increased. Clearly for the BER range considered here, the use of fixed window size N and frame length l (non-optimal) has more significant impact on throughput deterioration than the turnaround time, provided $t_{ta} < 0.01$ ms. Therefore for non-optimum values of N and l, the minimum turnaround time could be as high as 0.01 ms for $N = 7$ before throughput is affected. However, throughput is far from maximum when N and l are not adapted to their optimum values. In the next Section we examine the minimum turnaround time desired when the appropriate optimum values of N and l are used. The required link

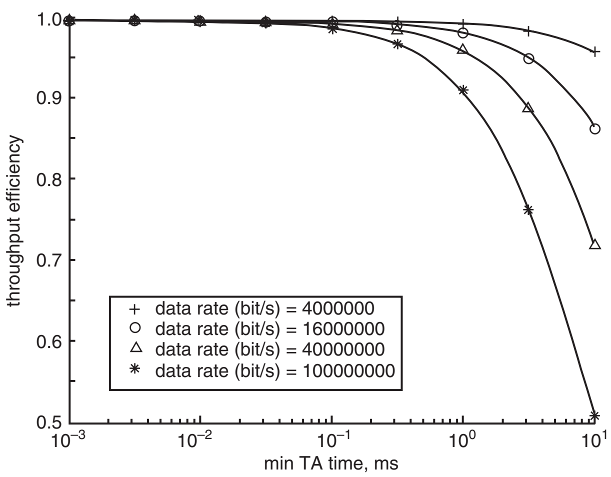

Fig. 3 *Effect of minimum turnaround time on throughput for $N = 127$, BER $= 10^{-9}$*

Packet size = 16384 bits; maximum TA time = 500 ms

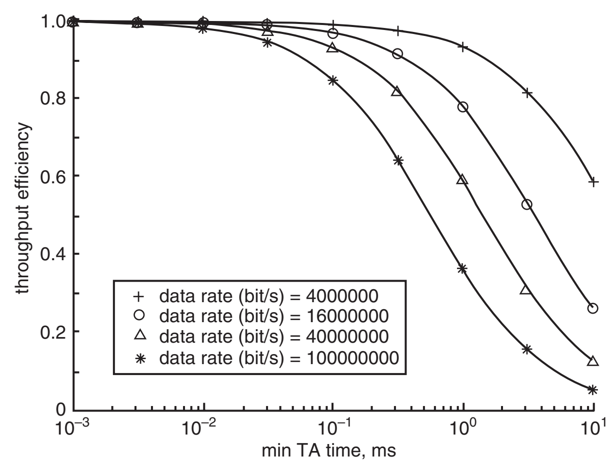

Fig. 5 *Effect of minimum turnaround time on throughput for $N = 7$, BER $= 10^{-9}$*

Packet size = 16384 bits; maximum TA time = 500 ms

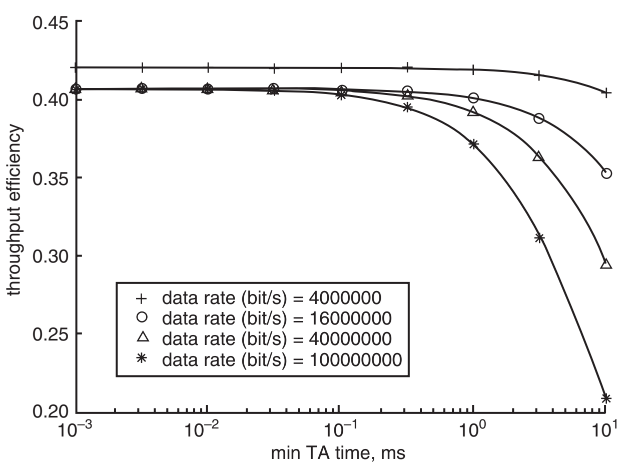

Fig. 4 *Effect of minimum turnaround time on throughput for $N = 127$, BER $= 10^{-6}$*

Packet size = 16384 bits; maximum TA time = 500 ms

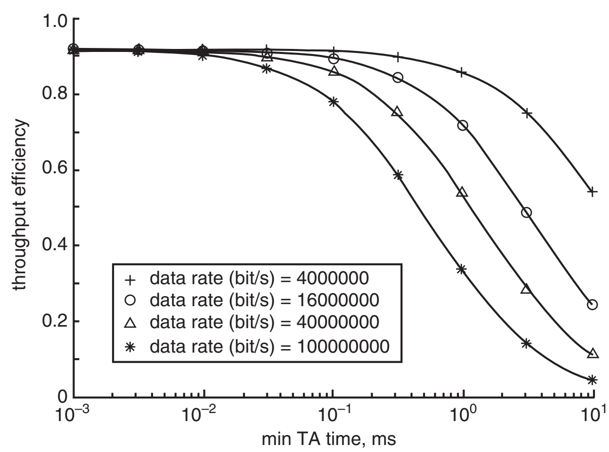

Fig. 6 *Effect of minimum turnaround time on throughput for $N = 7$, BER $= 10^{-6}$*

Packet size = 16384 bits; maximum TA time = 500 ms throughput is then higher even in situations when the link experiences high BER.

7 Minimum turnaround time of high data rate IrLAP links using optimum values of *N* and *l*

The effect of minimum turnaround time for IrDA links of data rates up to 100 Mbit/s designed to be robust to high BER is examined in this section. As described in the previous Sections, this is achieved by using simultaneous optimum *l* and *N* values for any BER. Figures 7–10 show the IrLAP throughput efficiency against minimum turnaround time, with BER as a parameter taking typical values $10^{-5}, 10^{-6}, 10^{-7}$ and 10^{-8}. The data rates considered are 4, 16, 40 and 100 Mbit/s reflecting existing and possible future data rates for IrDA links. It is clear that for all data rates reducing t_{ta} improves throughput. The throughput improvement obtained by reducing t_{ta} depends on the BER and improvement saturation occurs below a certain value of t_{ta}. As expected, using optimum *l* and *N* values, the links achieve higher throughput. This is clear by comparing corresponding curves in Figs. 3–6 and Figs. 7–10.

It is clear that 4 Mbit/s links using simultaneously optimum *N* and *l*, would benefit from $t_{ta} = 0.01$ ms (Fig. 7). This is an order of magnitude lower than the value the IrDA standard specifies. The links require an adaptive link layer with variable *N* and *l* as per approach 2 in this paper.

Similarly, in Fig. 8 for 16 Mbit/s links, $t_{ta} = 0.01$ ms would double throughput at high error rates when simultaneously optimum values of *N* and *l* are used when compared to the maximum throughput possible using the existing values of the IrDA standard. For future higher data rate links, say 40 Mbit/s, Figure 9 shows that a t_{ta} value between 0.01 and 0.001 ms would be desired. Finally, for

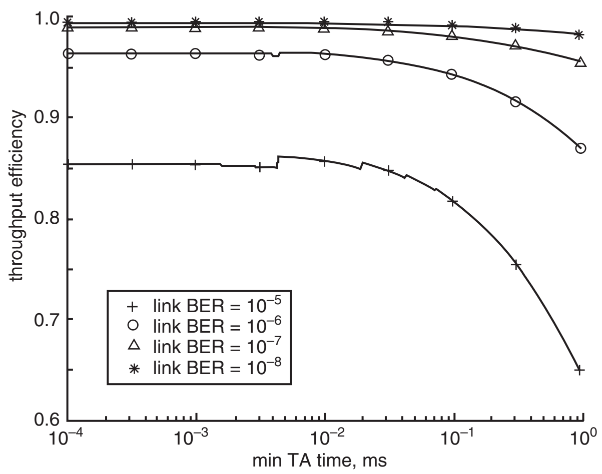

Fig. 7 *Effect of minimum turnaround time on throughput for 4 Mbit/s*

Maximum TA time = 500 ms

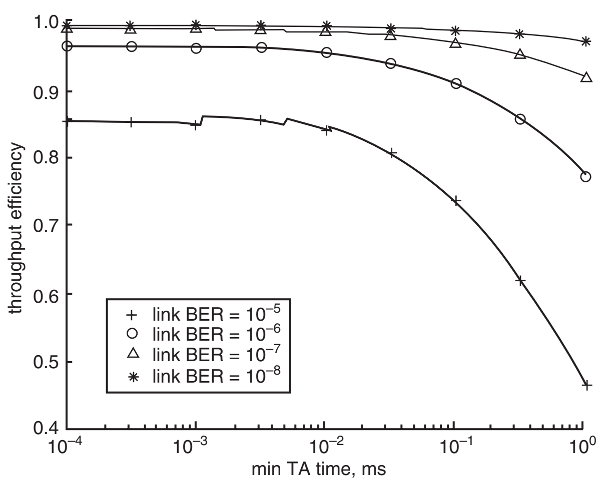

Fig. 8 *Effect of minimum turnaround time on throughput for 16 Mbit/s*

Maximum TA time = 500 ms

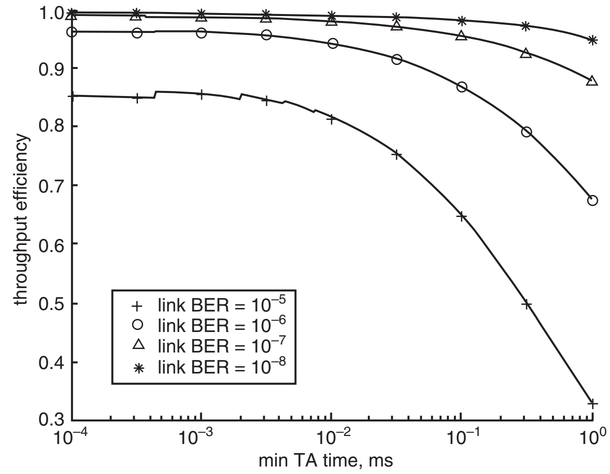

Fig. 9 *Effect of minimum turnaround time on throughput for 40 Mbit/s*

Maximum TA time = 500 ms

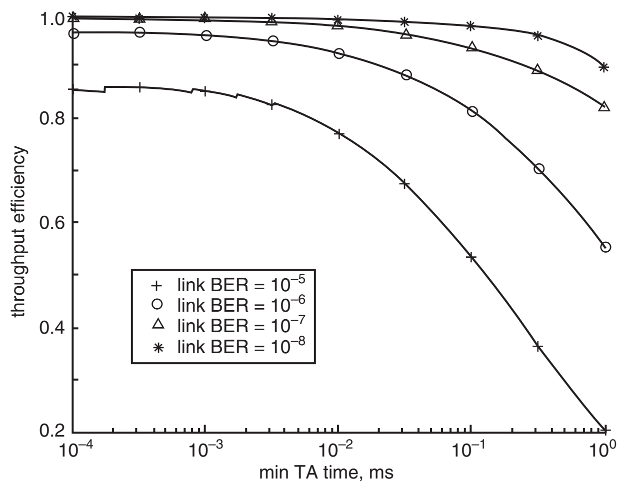

Fig. 10 *Effect of minimum turnaround time on throughput for 100 Mbit/s*

Maximum TA time = 500 ms

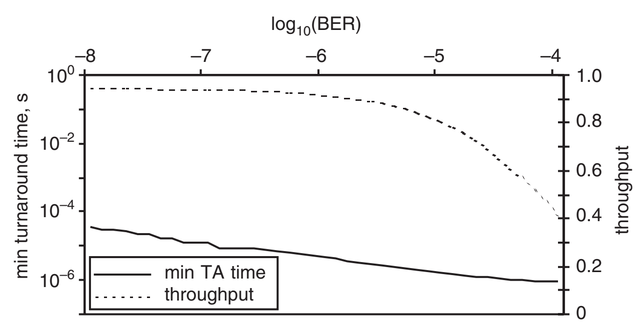

Fig. 11 *Required minimum turnaround time and maximum throughput for any BER, when $t_{Fout} = t_{Imax} + t_{ta}$ for 100 Mbit/s*

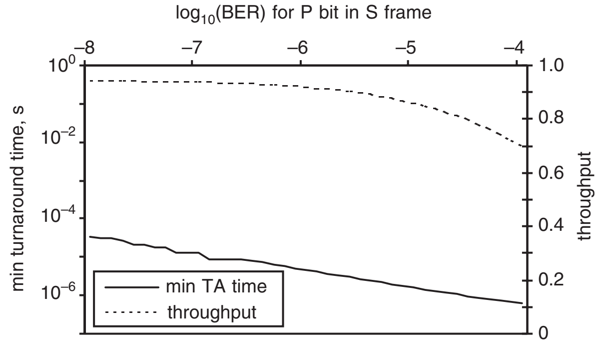

Fig. 12 *Required minimum turnaround time and maximum throughput for any BER for 100 Mbit/s*

100 Mbit/s links, as shown in Fig. 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 100 Mbit/s. This result is clearly shown in Fig. 11, where the relation of throughput and required minimum turnaround for any BER is shown for 100 Mbit/s IrLAP links. Figure 11 was derived by working out the required value of t_{ta} for 5% drop in throughput from the throughput of $t_{ta} = 10^{-4}$ ms as a reference. It is reasonable to assume here that at $t_{ta} = 10^{-4}$ ms the throughput is saturated to a maximum value for the data rates considered here. The value of t_{Fout} was defined as $t_{Fout} = t_{Imax} + t_{ta}$.

As it will become more obvious in the next Section at low t_{ta}, the value of t_{Fout} begins to play a more pronounced and eventually limiting role on throughput.

In order to deal with the effect of t_{Fout}, we also examine a technique [18] which minimises the effect of t_{Fout} to zero and improves throughput even further. This is achieved by setting the P bit in a special S frame [18]. In such cases, the result of the required t_{ta} for a drop to 95% of maximum throughput for any BER is shown in Fig. 12. The Figure also shows that the link requires t_{ta} approaching 10^{-6}. However, it offers even higher throughput efficiencies than those achieved with non-zero t_{Fout}, as shown in Fig. 11.

8 Effect of minimum turnaround time on throughput of 100 Mbit/s links using optimum link *N* and *l* values

In this Section the IrLAP throughput efficiency against BER of 100 Mbit/s links using the simultaneously optimal N and l values is presented. Figures 13–17 plot throughput efficiency using t_{ta} as a parameter; t_{ta} varies from 0.1 ms

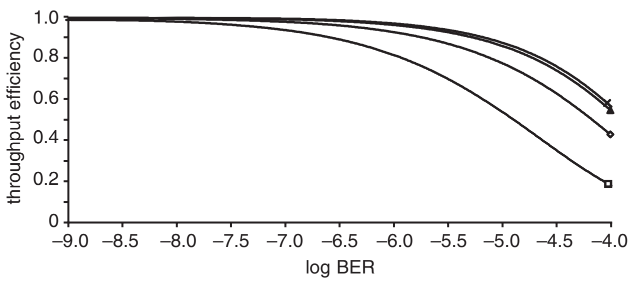

Fig. 13 *Throughput efficiency for 100 Mbit/s links using simultaneously optimum N and l values and t_{ta} varying from 0.1 ms to 0.1 µs*

□ $t_{ta} = 0.1$ ms, useful data transmission (throughput efficiency)
◇ $t_{ta} = 0.01$ ms, useful data transmission (throughput efficiency)
▲ $t_{ta} = 0.001$ ms, useful data transmission (throughput efficiency)
× $t_{ta} = 0.1$ µs, useful data transmission (throughput efficiency)

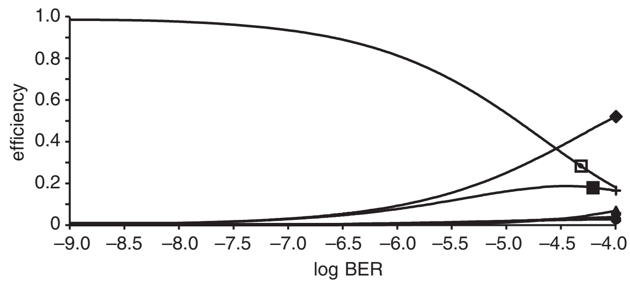

Fig. 14 *Throughput efficiency of 100 Mbit/s links and efficiency taken by other IrLAP tasks using simultaneously optimum N and l values, $t_{ta} = 0.1$ ms*

□ 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
× transmission of frame overheads l'

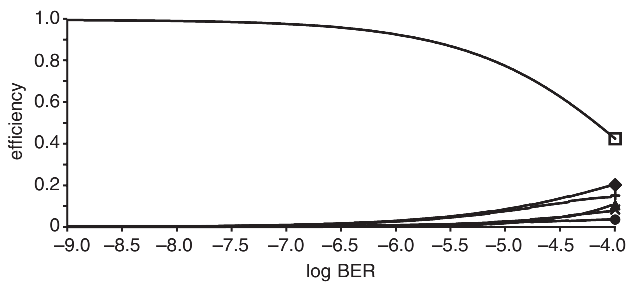

Fig. 15 *Throughput efficiency of 100 Mbit/s links and efficiency taken by other IrLAP tasks using simultaneously optimum N and l values, $t_{ta} = 0.01$ ms*

□ 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
× transmission of frame overheads l'

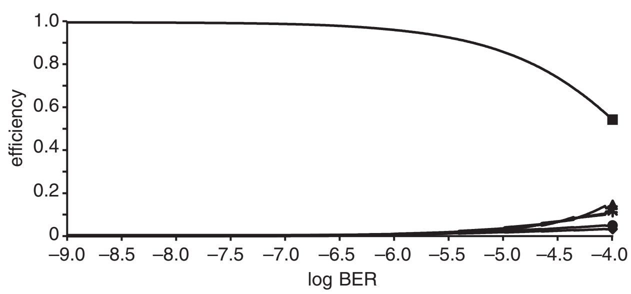

Fig. 16 *Throughput efficiency of 100 Mbit/s links and efficiency taken by other IrLAP tasks using simultaneously optimum N and l values, $t_{ta} = 0.001$ ms*

■ useful data transmission (throughput efficiency)
+ retransmission of correctly received out of sequence frames
● retransmission of error frames
▲ t_{Fout} timer expiration
◆ t_{ack} time of frames
× transmission of frame overheads l'

to 0.0001 ms. Figure 13 plots throughput efficiency versus BER. It shows that if $t_{ta} = 0.1$ ms (the t_{ta} value proposed in the IrDA standard), throughput efficiency is very low at high BER. If t_{ta} is reduced to 0.01 ms and 0.001 ms, significant throughput increase is observed at low BER. Further t_{ta} reduction to 0.1 µs results in negligible throughput increase, verifying the result Fig. 10 indicated.

Figures 14–16 examine the effect of turnaround time on throughput efficiency by plotting, in addition to throughput

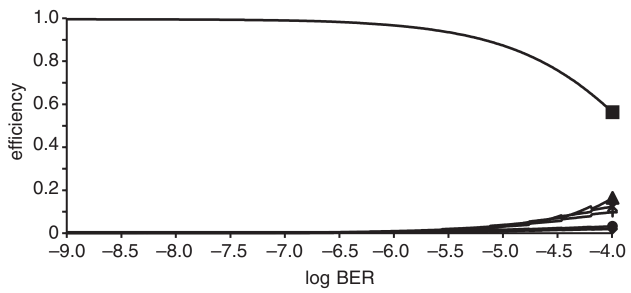

Fig. 17 *Throughput efficiency of 100 Mbit/s links and efficiency taken by other IrLAP tasks simultaneously optimum N and l values, $t_{ta} = 0.1\ \mu s$*

■ useful data transmission (throughput efficiency)
+ retransmission of correctly received out of sequence frames
● retransmission of error frames
▲ t_{Fout} timer expiration
◆ t_{ack} time of frames
× transmission of frame overheads l'

efficiency, the efficiency loss (time wasted for other tasks of the protocol, than useful data transfer, based on (10)–(14)). These efficiency-detrimenting tasks always have an increasing negative effect on the throughput with increasing BER. Figures 14–16 are shown for decreasing values of t_{ta}.

It can be seen in Fig. 14 that $t_{ta} = 0.1$ ms, which contributes significantly to t_{ack}, produces the most significant component of efficiency detriment for high BER. Reducing t_{ta} to 0.01 ms in Fig. 15, the t_{ack} component is significantly lowered and as a result, the overall throughput efficiency is increased to approximately 0.4 for BER = 10^{-4}. Further reduction of t_{ta} to 0.001 ms (Fig. 16) improves the throughput efficiency to approximately 0.6 for BER = 10^{-4} (confirming the result of Fig. 10) and eliminates the significance of t_{ack}. Finally, loss of efficiency due to t_{Fout} becomes significant and resistant to t_{ta} even for $t_{ta} = 0.0001$ ms (Fig. 17) Therefore, in order to improve further the throughput efficiency subsequent to reducing the t_{ta}, a reduction in t_{Fout} is the one that would have a positive effect. From Fig. 17, we deduce that reducing t_{ta} from 1 to 0.1 μs does not improve throughput significantly due to the resistant t_{Fout} component and it is not therefore necessary.

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

9 Conclusions

The performance of IrDA IrLAP protocol operating at a data rate of 100 Mbit/s has been examined. Such a high data rate may be 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 utilising simultaneously optimal values for N and l. The performance results indicate that a turnaround time of less than 1 μs would yield excellent throughput results. The optimal values for N and l are in accordance with simple equations, which are derived from first principles. Adjusting the window and frame lengths ensures high throughput at the link layer even at high BER.

It is concluded that the IrLAP protocol is not a limitation to increasing the IrDA data rates to 100 Mbit/s. This is possible provided that PHY layer hardware of appropriate turnaround time and BER at the required data rate can be built. Adaptive change of N and l yields optimum high link layer throughput over a wide BER range.

10 References

1 Williams, S.: 'IrDA: Past, present and future', *IEEE Pers. Commun.*, Feb. 2000, **7**, (1), pp. 11–19
2 Knutson, C., Joos, D., and Woodings, R.: 'Infrared data communications in wireless personal area networks'. Proc. 5th World Multiconference on Systemics, Cybernetics and Informatics, Orlando, FL, 22–25 July 2001, vol. IV, pp. 427–431
3 Ghassemlooy, Z., and Hayes, A.R.: 'Digital pulse interval modulation for IR Communications systems, a review', *Int. J. Commun. Syst.*, 2000, **13**, (special issue), pp. 519–536
4 Vitsas, V., and Boucouvalas, A.C.: 'Performance evaluation of IrDA advanced infrared AIR-MAC protocol'. Proc. 5th World Multiconference on Systemics, Cybernetics and Informatics, Orlando, USA, 22–25 July 2001, vol. IV, pp. 347–352
5 IrDA: 'Serial Infrared Physical Layer Specification for 16 Mbit/s Addition (VFIR) – Errata to version 1.3', Infrared Data Association, 1999
6 IrDA: 'IrBurst High-speed Object Transmission Profile – Version 0.1', Infrared Data Association, 2002
7 IrDA: 'Serial Infrared Link Access Protocol (IrLAP) – Version 1.1', Infrared Data Association, 1996
8 Lin, S., Costello, D.J., and Miller, M.: 'Automatic-repeat-request error-control schemes', *IEEE Commun. Mag.*, Dec. 1984, **22**, (12), pp. 5–17
9 Benelli, G.: 'A go-back-N protocol for mobile communications', *IEEE Trans. Veh. Technol.*, Nov. 1991, **40**, (4), pp. 714–720
10 Bux, W., Kummerle, K., and Truong, H.L.: 'Balanced HDLC procedures: a performance analysis', *IEEE Trans. Commun.*, 1980, **28**, pp. 1889–1898
11 Vitsas, V., and Boucouvalas, A.C.: 'IrDA IrLAP protocol throughput performance analysis for optical wireless links'. Proc. IEEE 2nd Int. Workshop on Networked appliances (IWNA 2000), Rutgers Univ., New Jersey, USA, 30 Nov.–1 Dec. 2000
12 Barker, P., Boucouvalas, A.C., and Vitsas, V.: 'Performance modelling of the IrDA Infrared Wireless Communications Protocol', *Int. J. Commun.*, 2000, **13**, pp. 589–609
13 IrDA: 'Serial Infrared Physical Layer Specification (IrPHY) – Version 1.3', Infrared Data Association, 1998
14 IrDA: 'Serial Infrared Physical Layer Specification – Version 1.0', Infrared Data Association, 1994
15 IrDA: 'Serial Infrared Physical Layer Specification – Version 1.1', Infrared Data Association, 1995
16 Boucouvalas, A.C., and Vitsas, V.: 'Optimum window and frame size for IrDA links', *Electron. Lett.*, 2001, **37**, (3), pp. 194–196
17 Vitsas, V., and Boucouvalas, A.C.: 'Window and frame size adaptivity for maximum throughput in IrDA links'. Proc. 3rd Electronic Circuits and Systems Conference, Slovak University of Technology in Bratislava, Bratislava, Slovakia, 5–7 September 2001, pp. 147–152
18 Vitsas, V., and Boucouvalas, A.C.: 'Simultaneous optimisation of window and frame size for maximum throughput IrDA links', *Electron. Lett.*, 2001, **37**, (16), pp. 1042–1043