CHAPTER 3

Performance of Infrared Data Link Layer

The performance of indoor infrared point-to-point links is affected by the half-duplex operation, by the time required to reverse link direction and by transmission errors introduced by the wireless medium. Infrared noise at the receiver arising from the sun and artificial lighting may degrade link quality. The required alignment and link distance can not be always met. In addition, the obstruction of the line of sight path between the transmitter and the receiver reduces the performance of the infrared link.

IrLAP, which drives the infrared hardware, implements a Go-Back-N retransmission scheme to cope with transmission errors. To reduce delays arising from frame overheads, IrLAP may implement large frame sizes. The transmitter may also transmit a window of frames before reversing link direction and soliciting an acknowledgment form the receiver in order to reduce delays arising from frequent link turn around. This chapter considers design issues for efficient operation of the IrLAP layer. It develops a mathematical model that reaches a simple closed form equation for the IrLAP utilization. This formula allows easy calculation of IrLAP utilization and allows a better intuitive understanding of IrLAP performance.

The outline of this chapter is as follows. Section 3.1 presents the IrDA 1.x protocol stack and section 3.2 describes the IrLAP layer, the parameters it negotiates for efficient link operation and the IrLAP frame structure. Section 3.3 presents the considered information exchange model. A mathematical model that evaluates IrLAP utilization by calculating the average window transmission time is developed in section 3.4 and section 3.5 validates the proposed model. Section 3.6 presents an IrLAP performance evaluation focusing on the proposed 16 Mbit/s data rate. Finally, section 3.7 discusses physical and link layer parameter selection for the predicted future increases in IrDA 1.x data rates.

3.1 IrDA 1.x protocol stack

The IrDA architecture is presented in Fig. 3.1. IrPHY ver. 1.0 Serial Infrared (SIR) [50] defines hardware specifications for 2.4 Kbit/s to 115.2 Kbit/s data rates using conventional serial UART chips. It employs RZI modulation scheme and a ‘0’ is

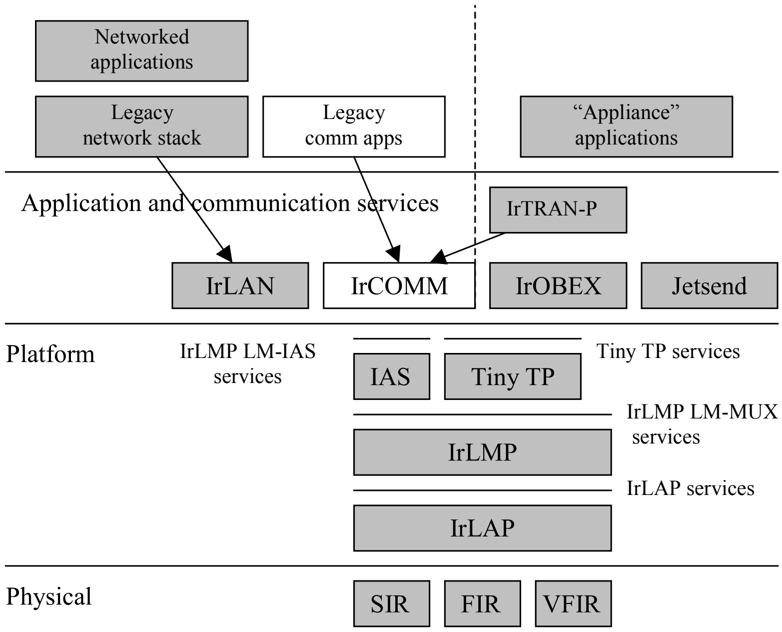


Figure 3.1 The IrDA protocol architecture

represented by a light pulse. The optical pulse duration is nominally 3/16 of a bit duration and the maximum receiver latency allowance is 10ms. The bit error rate (BER) must be less than 10^{-9}. IrPHY ver. 1.1 Fast Infrared (FIR) [51] introduced the 0.576 Mbit/s and 1.152 Mbit/s data rates employing RZI modulation and the 4Mbit/s data rate employing 4PPM modulation scheme. It also allowed higher link error rates by specifying that the link BER should be less than 10^{-8}. Very fast Infrared (VFIR) specification [53] added the 16Mbit/s data rate by using a newly developed HHH(1,13) code [37] and reduced the allowable receiver latency to 0.1ms. IrPHY specifies a link distance of at least 1m and an off axis angle of ±15 to ±30 degrees [67][52]. The IrDA Link Access Protocol (IrLAP) is the data link layer of the IrDA protocol stack [49]. It provides a fixed rate (9,600 bit/s) slotted contention mode for device discovery and parameter negotiation. After initial contact, it defines contention-free access to the IR medium by using master station control. The Link Management Protocol consists of the Link Management Multiplexer (LM-MUX) and the Link Management Information Access Service (LM-IAS) [48]. LM-MUX is a connection oriented multiplexer that allows multiple applications in an IrDA device to communicate over a single IrLAP connection and LM-IAS facilitates discovery of services available by the communicating device. An IrDA service claims an LM-MUX port and advertises itself to the communicating device by placing its service information and necessary parameters in a lookup table. Implementation of IrPHY, IrLAP and IrLMP is required from all IrDA-compliant devices. TinyTP is a useful light-weight transport protocol for segmentation and reassembly operations and for application level flow control. IrCOMM is the cable replacement of the IrDA stack. IrCOMM is a serial and parallel port emulation protocol, enabling all applications designed to operate over serial or parallel ports to operate unchanged over the infrared medium. IrCOMM allows both DTE-DTE (null modem) and DTE-DCE connections. IrLAN allows station LAN access over an IrDA link and IrOBEX is the IrDA HTTP protocol, facilitating simple data object (business card, phone list) exchange. IrTRAN-P allows the exchange of images between digital cameras, photo printers and PCs while IrJetSend allows IrDA binding to Hewlett-Packard Jetsend protocol [5][67][101].

3.2 IrLAP layer

IrLAP design is based on the pre-existing HDLC and SDLC protocols [101]. The functions of IrLAP include device discovery, link establishment, data exchange and error recovery [49]. IrLAP stations operate in two modes; in the Normal Disconnect Mode (NDM) during the contention period and in the Normal Response Mode (NRM) during the connection period. During the contention period, a station advertises its existence to all stations within its transmission range along with the physical and link layer parameters it supports and wishes to use during the information exchange procedure. IrLAP assigns primary and secondary roles in NDM; one of the participating stations is assigned the primary role and all remaining stations are assigned the secondary role. Any station may claim to become the primary station but only one wins the contention. In NRM mode (connection period), only transmissions to or from the primary station are permitted. If a secondary station wishes to communicate with another secondary station, it does so through the primary station. In NDM mode, communicating stations also determine the best connection capability that can be supported by both stations; they negotiate and agree on the following parameters to be used in NRM mode (connection period):

a) *Data rate (C)*. This parameter specifies the station's transmission rate.
b) *Maximum turn around time (T_{max})*. This parameter specifies the maximum time period a station can hold transmission control. IrLAP specifies that T_{max}=500ms for data rates less than 115.2 Kbit/s but smaller values may be agreed for the 115.2

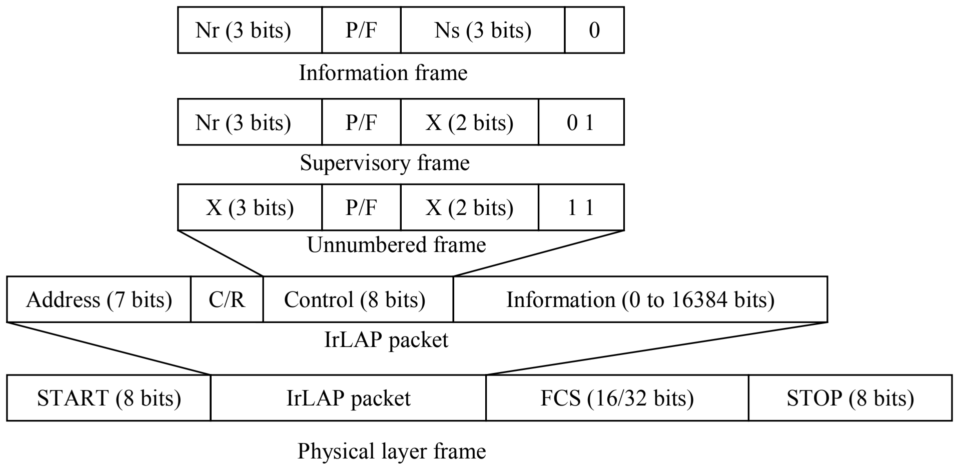


Figure 3.2 IrDA SIR and FIR frame structure

Kbit/s or higher data rates.

c) *Data size (l)*. This parameter specifies the maximum size of the data field of any received Information frame (I-frame). IrLAP supports a maximum data size value of 2,048 bytes (16Kbits).

d) *Window size* (W_{max}). This is the maximum number of unacknowledged I-frames a station can receive before it has to transmit an acknowledgement. The transmitting station may request an acknowledgement before the window size is reached. IrLAP specifies that W_{max} has an upper limit of 7 for data rates up to 4Mbit/s and 127 for the 4Mbit/s and 16Mbit/s data rates [49][53].

e) *Minimum turn around time* (t_{ta}). This is the time period needed by the receive circuit to recover after the end of a transmission originated from the same station, as explained in section 2.5(c). This is the time required to reverse link direction.

Parameters (b), (c), (d) and (e) are negotiated and agreed independently for each station. However, both stations must agree and use the same data rate (parameter (a)).

Fig. 3.2 presents the IrDA 1.x frame structure. A frame consists of the START flag, the IrLAP packet, the frame check sequence (FCS) field and the STOP flag. The FCS field contains a 16-bit CRC for data rates lower than 4Mbit/s and a 32-bit CRC for the 4Mbit/s and higher data rates.

IrLAP specification defines the following frame types (Fig. 3.2):

a) Unnumbered frames (U-frames): U-frames are employed for link management. They are used to exchange connection data, to discover and initialize secondary stations and to report procedural errors that can not be recovered by retransmissions.

b) Supervisory frames (S-frames): S-frames contribute in the information exchange procedure although they never carry information data themselves. S-frames are used to report frame sequencing errors, to acknowledge correctly received frames and to request an acknowledgement from the remote station.

c) Information frames (I-frames): I-frames carry information data to the remote station during the connection period. I-frames are sequenced to ensure that they are received in the correct order by the receiver.

Every frame has a control field. The control field always contains a frame identifier, which determines the frame type and the P/F bit, which is used to pass transmission control. The control field of I-frames (Fig. 3.2) contains a send sequence number, N_s, used to number the transmitted I-frames. I-frame and S-frame control field contains a receive sequence number, N_r, which is used to indicate the expected sequence number of the next I-frame. S-frame and U-frame control field contains the command/response code, *X*, of the frame. SIR and FIR specifications define an 8-bit control field (Fig. 3.2). N_s and N_r occupy 3 bits each, N_s and N_r cycle through values from 0 to 7 and maximum window size is 7. VFIR specification extended the length of the control field to 16 bits for the 4 Mbit/s and 16 Mbit/s data rates. In 16-bit control fields, N_s and N_r are 7 bits each, they cycle through values 0 to 127 and a maximum window size of 127 is supported.

The control field always contains the P/F bit, which implements token passing between the communicating stations. When it is set by the primary station, it is the poll (P) bit. When it is set by the secondary, it is the final (F) bit. When the P/F bit is set, the link direction is reversed. Primary sets the P-bit to solicit a response or sequence of responses from the secondary. When the secondary receives a frame with the P-bit set, it responds by transmitting one or more frames. The secondary also sets the F-bit of the last frame it transmits to reverse link direction and return transmission control to the primary station. Thus, the secondary stations have transmission control only when they are transmitting frames to the primary [49].

IrLAP stations also employ the P-timer. The P-timer is assigned with the maximum turn around time (T_{max}) agreed between the two stations during the contention period

(NDM mode). As T_{max} stands for the maximum time the station can hold transmission control, the station starts the P-timer when it receives a frame with the P/F bit set and stops the P-timer when it transmits a frame with the P/F bit set. If P-timer expires, meaning that the station has already held transmission control long enough, it immediately transmits a Receive Ready (RR) S-frame with the P/F bit set to pass transmission control.

The primary station also employs an F-timer to limit the time a secondary station can hold transmission control. The primary starts the F-timer upon transmission of a frame with the P-bit set and stops the F-timer upon reception of a frame with the F-bit set. F-timer expiration means that the secondary failed to return transmission control within the agreed time period. Since the secondary's P-timer operation guarantees that this never happens, F-timer expiration can only be explained by the loss of either the frame that contained the P-bit or the frame that contained the F-bit. The primary resolves this situation by transmitting a RR frame with the P-bit set when the F-timer expires.

3.3 Functional model description

This work considers the transmission of a large amount of information data between two stations because IrDA links are usually employed for information transfer from one device to another. The saturation case is studied, in which the transmitter always has information data ready for transmission. Typical practical examples of the considered scenario are (a) the picture downloading form a digital photo camera to a laptop computer for processing, (b) the downloading of data from a portable information gathering appliance to a host computer, (c) the transferring of a phone list from a mobile phone to a computer or to another mobile phone and (d) the printing from a laptop to a (usually inkjet) printer.

In the considered scenario, only two stations form the infrared WPAN, the primary station and only one secondary station. It is assumed that the transmitting station claimed and was finally granted the primary role during the contention period. It is also assumed that transmission errors follow a random distribution.

The parameters used in the current model are shown in Table 3.1. In the contention period (negotiation stage), the primary station determines the window size N it will employ. N represents the maximum number of I-frames the primary can transmit before

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
U	Utilization	-

Table 3.1: Parameters used in modeling IrLAP utilization

soliciting an acknowledgement. Maximum window size parameter W_{max} is negotiated and agreed between the two stations in the contention period. However, the maximum time a station can hold transmission control, T_{max}, must always be obeyed and, according to IrLAP specification [49], T_{max} has a higher priority than W_{max}. T_{max} combined with the implemented frame size and link data rate may limit the window size applied. In other words, if the time needed for transmitting W_{max} frames carrying 'frame size' information bytes at the link data rate exceeds T_{max}, then a smaller window size must be implemented. Thus, N is given by

$$N = min\left\{W_{\max}, floor\left(\frac{T_{max}}{t_I}\right)\right\} \tag{3.1}$$

where *min* is 'the lesser of' and *floor* is 'the largest integer not exceeding'. In this work, T_{max} is always fixed at 500 ms.

IrLAP utilizes a Go-Back-N retransmission scheme and retransmits the correctly received frames that follow an error frame in a window transmission. The information transfer procedure used in the current model is presented in Fig. 3.3. Each node holds three variables, V_s for counting the transmitted frames, V_r for counting the received frames and w indicating the number of the remaining I-frames the station can transmit before reversing link direction [91]. The primary also employs an F-timer that limits the secondary's transmission period.

The primary station acts as follows. When it prepares an I-frame, the N_s sub-field of the frame's control field is assigned the current V_s value and V_s is increased by 1

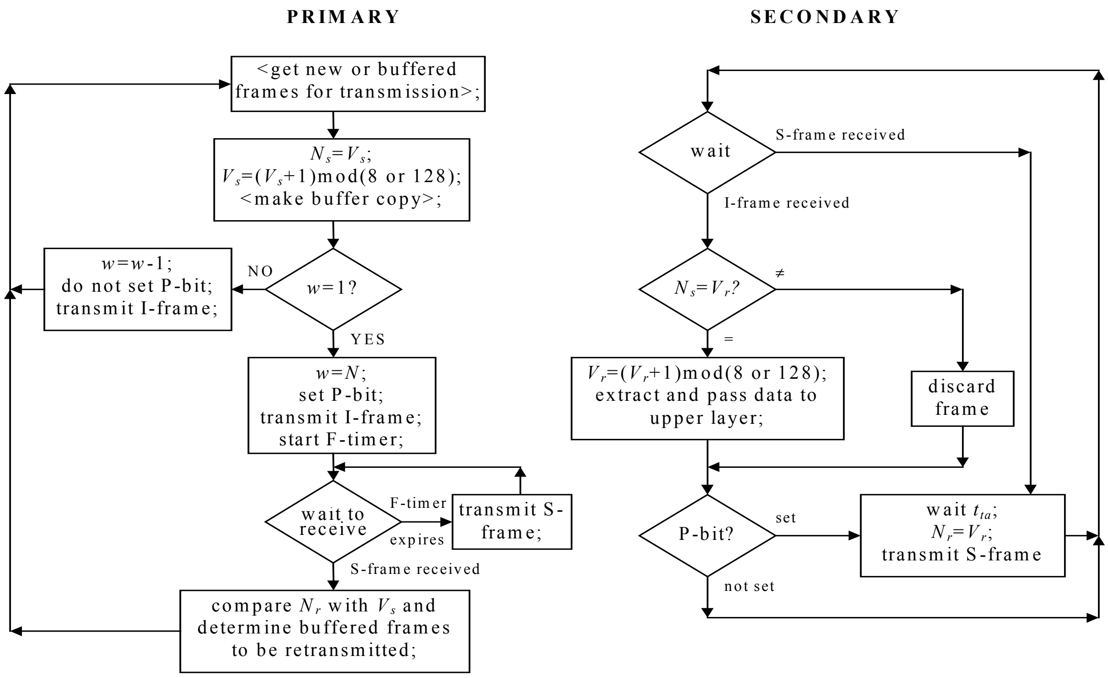


Figure 3.3 Information transfer procedure

(modulo 8 or 128 depending on control field size employed). The primary also makes a buffer copy of the frame for possible retransmissions. Since the primary always has I-frames ready for transmission, it immediately checks the *w* value. If *w* is not equal to 1, primary reduces *w* by 1, transmits the I-frame with the P-bit not set and repeats the actions previously described. When *w* reaches 1, indicating that the next I-frame should be the last frame in the window transmission, the primary sets the P-bit to poll the secondary and transmits the I-frame. The primary also assigns *N* to *w* for the next *N* window frame transmission and starts the F-timer.

The secondary node acts as follows. When it receives an I-frame, it compares the received frame sequence N_s value with station's expected V_r value. If N_s equals V_r (the received frame is in sequence), V_r is increased by 1 (modulo 8 or 128) and information data is extracted and passed to the upper layer. If the received frame is not in sequence (one of the previous I-frames in current window transmission was lost due to a CRC detected error), the frame is discarded and V_r remains unchanged. The secondary also checks the P-bit. If the P-bit is set and as the current model assumes that the secondary station never has information data for transmission, it awaits a *minimum turn around time* t_{ta} to allow for the primary's hardware recovery latency and transmits an S-frame with the F-bit set. The S-frame's N_r field is assigned the V_r value informing the primary of the number of I-frames received correctly and in sequence in the previous window transmission. When the primary receives the S-frame, it resumes I-frame transmission as transmission control was returned to the primary by means of the F-bit. The primary first compares the received S-frame's N_r with current V_s value. If N_r equals to V_s (all I-frames in the previous window transmission were received correctly by the secondary), the primary transmits I-frames containing new information data to the secondary. If N_r is not equal to V_s, one or more I-frames in the previous window transmission are lost. The primary retransmits buffered I-frames starting from the indicated N_r position before transmitting new I-frames.

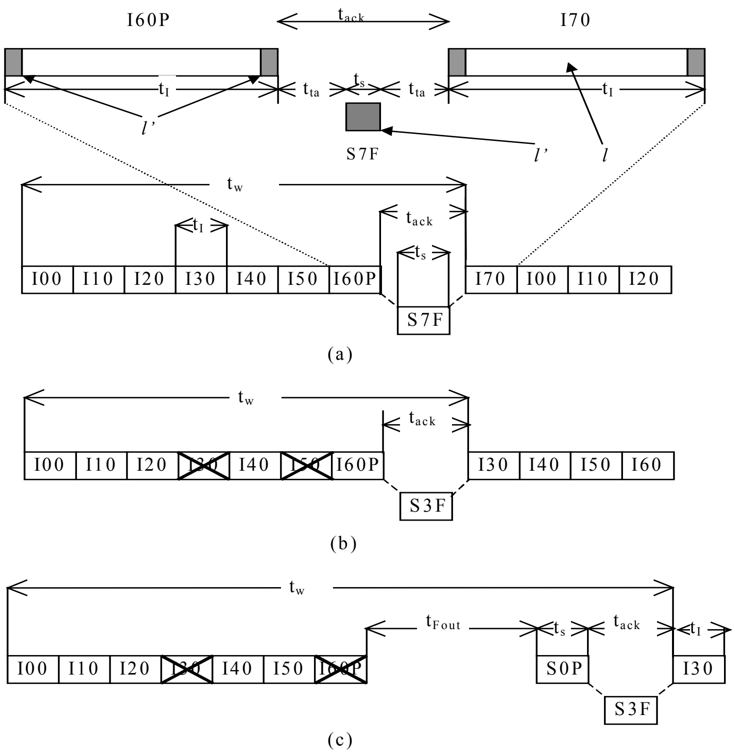
If the last I-frame that contains the P-bit is lost, the secondary station fails to respond, as it does not realize that it has transmission control. The situation is resolved by primary's F-timer expiration. The primary realizes that the secondary failed to respond during the agreed time period and transmits an S-frame forcing the secondary to respond. In the current model, S-frames are considered small enough to be always received error free.

The saturation model considered in this work can be summarized as follows. The transmitting station always has information ready for transmission. As a result, it transmits a window of N consecutive I-frames and reverses the link direction by setting the P-bit in the last I-frame. The receiver awaits a minimum turn around time (t_{ta}) and responds with a Receive Ready (RR) S-frame indicating the next frame expected. The RR frame always has the F-bit set. The transmitter determines the number of frames correctly received before any error(s) occurred and repeats the erred frame and the frames following it, in the next window, followed by new frames to form a complete N frame transmission. If the last frame in a window transmission is lost, the receiver fails to respond as the P-bit is lost. When the F-timer expires, the primary station sends a RR S-frame with the P-bit set forcing the secondary station to acknowledge correctly received frames [92].

3.4 IrLAP mathematical model

The values for t_S, t_I, t_{ack}, p and U are given by (Fig. 3.4):

$$t_S = \frac{l'}{C} \tag{3.2}$$



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*
(a) *Window error free transmission*
(b) *Retransmitted frames due to error frame with* N_s *=3 and* N_s *=5*
(c) *Retransmitted frames and F-timer delay due frame error at* N_s *=3 and* N_s *=6*

Figure 3.4 Determination of window transmission time t_w

$$t_I = \frac{l + l'}{C} \tag{3.3}$$

$$t_{ack} = 2t_{ta} + t_s \tag{3.4}$$

$$p = 1 - (1 - p_b)^{l+l'} \tag{3.5}$$

$$U = \frac{l}{C} D_f \tag{3.6}$$

This model uses the term "window transmission time" (WTT) to denote the average time needed for a complete window frame transmission and for the acknowledgments and delays concerning this transmission. WTT accounts for the time taken from the start of the first frame in a window transmission to the start of the first frame in the next window transmission. WTT incorporates time utilized in I-frame transmissions, in acknowledgments, in reversing link direction and in possible timer time out delays.

As shown in Fig. 3.4, the key issue that determines WTT is the reception status of the last I-frame in the window, the frame that contains the P-bit. If this frame is correctly received and regardless of the existence of previous errors, (Fig. 3.4(a)&(b)), WTT t_w is given by

$$t_w = Nt_I + t_{ack} \tag{3.7}$$

If the last I-frame that contains the P-bit is lost, an additional delay for the F-timer expiration and S-frame transmission t_s is introduced and WTT is independent of possible additional I-frame errors. This situation is shown in Fig. 3.4(c) and WTT is given by

$$t_w = Nt_I + t_{Fout} + t_s + t_{ack} \tag{3.8}$$

As an I-frame is incorrectly received with probability p, the average WTT is given by

$$t_w = Nt_I + p(t_{Fout} + t_s) + t_{ack} \tag{3.9}$$

Considering that all I-frames, that follow an I-frame incorrectly received in an N window frame transmission, are considered as out of sequence and are discarded by the receiver, the probability $p_c(w)$ that exactly w frames at the beginning of a window transmission are correctly in sequence received and are followed by an error frame in position (w+1) is

$$p_c(w) = (1-p)^w p, \quad w=0,1,2,\ldots,N-1 \tag{3.10}$$

The probability that all I-frames in a window transmission are correctly received is

$$p_c(N) = (1-p)^N \tag{3.11}$$

The expected number of correctly received frames, p_{all}, at the beginning of an N I-frame window transmission is

$$p_{all} = \sum_{w=0}^{N} wp_c(w) \tag{3.12}$$

Frame throughput D_f can now be found by dividing the expected number of frames correctly received in a window transmission, p_{all}, by the average WTT required for the window transmission

$$D_f = \frac{\sum_{w=0}^{N} wp_c(w)}{Nt_I + p(t_{Fout} + t_s) + t_{ack}} \tag{3.13}$$

After some algebra, (3.13) reduces to

$$D_f = \frac{1-p}{p} \cdot \frac{1-(1-p)^N}{Nt_I + p(t_{Fout} + t_s) + t_{ack}} \tag{3.14}$$

and by combining (3.6) with (3.14), link utilization is given by

$$\boxed{U = \frac{l}{C} \cdot \frac{(1-p)}{p} \cdot \frac{1-(1-p)^N}{Nt_I + p(t_{Fout} + t_s) + t_{ack}}} \tag{3.15}$$

An intuitive explanation of (3.14) is as follows. Term $(1-p)/p$ represents the expected number of frames correctly received before a frame error occurs. It counts for the frames from the first frame in a window transmission that follows a window containing an error to the next frame in error. Term $\left(1-(1-p)^N\right)$ is the probability that there is at least an error in a window transmission and term $Nt_I+p(t_{Fout}+t_s)+t_{ack}$ stands for the average WTT.

This analysis allows the evaluation of all component tasks affecting the IrLAP utilization. Such an evaluation reveals the main factors resulting in utilization degradation when IrLAP operates over high BER infrared links. Equation (3.15) can be rewritten as

$$U = \frac{l}{C} \cdot \frac{(1-p)}{p} \cdot \frac{1-(1-p)^N}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \tag{3.16}$$

Time portion attributed to acknowledgments T_{tack} is given by

$$T_{tack} = \frac{t_{ack}}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \tag{3.17}$$

Time portion used on P-bit loss and F-timer expiration T_{Fout} is given by

$$T_{Fout} = \frac{p(t_{Fout} + t_s)}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \tag{3.18}$$

Time portion taken on transmitting frame overheads l' is given by

$$T_{l'} = \frac{\frac{Nl'}{C}}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \tag{3.19}$$

As the expected number of error frames in a window transmission is pN, time portion spent on retransmission of error frames T_{error} is

$$T_{error} = \frac{\frac{pNl}{C}}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \quad (3.20)$$

The expected number of correctly transmitted frames following an error frame in a window transmission can be found if from the total number of frames in a window *N*, we subtract the error frames *pN* and the correct in sequence frames $\frac{(1-p)}{p}\left(1-(1-p)^N\right)$.

Thus the time portion spent on retransmitting correctly received out of sequence frames is given by

$$T_{corr} = \frac{\left(N(1-p) - \frac{(1-p)}{p}\left(1-(1-p)^N\right)\right)\frac{l}{C}}{N\frac{l+l'}{C} + p(t_{Fout} + t_s) + t_{ack}} \quad (3.21)$$

As all component tasks that affect IrLAP utilization are considered, equation

$$U + T_{tack} + T_{Fout} + T_{l'} + T_{error} + T_{corr} = 1 \quad (3.22)$$

always holds true. Eq. (3.22) can be easily verified from eq. (3.16)-(3.21).

3.5 Model validation

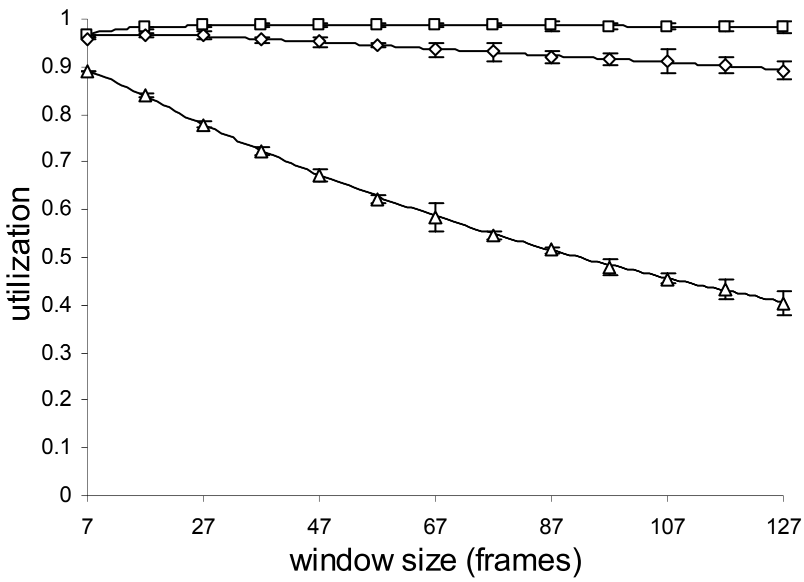
3.5.1 Comparison with simulation

To validate the above mathematical model, a set of simulation runs was performed using the OPNET™ simulation package [71]. The OPNET simulator emulates IrLAP station behavior as close as possible, including transmission times, turn around delays, transmission errors and timer expiration.

Fig. 3.5 plots utilization versus window size for different bit error rate (BER) p_b values. The analytical model is validated as its calculated utilization (lines) practically coincides with simulation results (points). Simulation results are obtained with a confidence interval of 98%.

3.5.2 Comparison with existing analytical models

The proposed analytical model is also validated using the existing analytical model presented in [4],[6]. This analytical model evaluates the IrLAP performance for the same information exchange scenario using the concept of a frame's virtual transmission time (VTT). However, the VTT concept leads to very complex algebraic expressions



□ $p_b=10^{-8}$ ◇ $p_b=10^{-7}$ △ $p_b=10^{-6}$

Figure 3.5 Analysis versus simulation: Utilization against window size, C=16Mbit/s, l=16Kbits, T_{max}=500ms, t_{ta}=0.1ms. Simulation confidence interval=98%

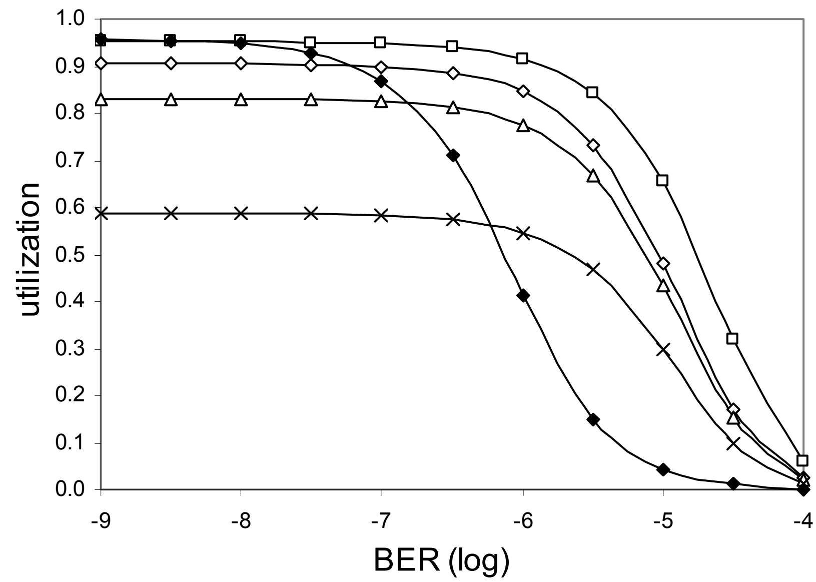
that calculate IrLAP utilization [6]. After considerable algebraic calculations, the existing model simplifies and reaches the same simple equation (3.15), thus validating the mathematical model developed in this work. An extensive discussion on IrLAP mathematical models can also be found at [99].

3.6 IrLAP performance evaluation

Equation (3.15) allows us to get an intuitive understanding of IrLAP performance. Three factors contribute to average WTT given in (3.9). 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 3.2 shows

specifi-cation	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

Table 3.2: Factors Nt_I and t_{ack} that contribute to t_w for SIR and FIR data rates

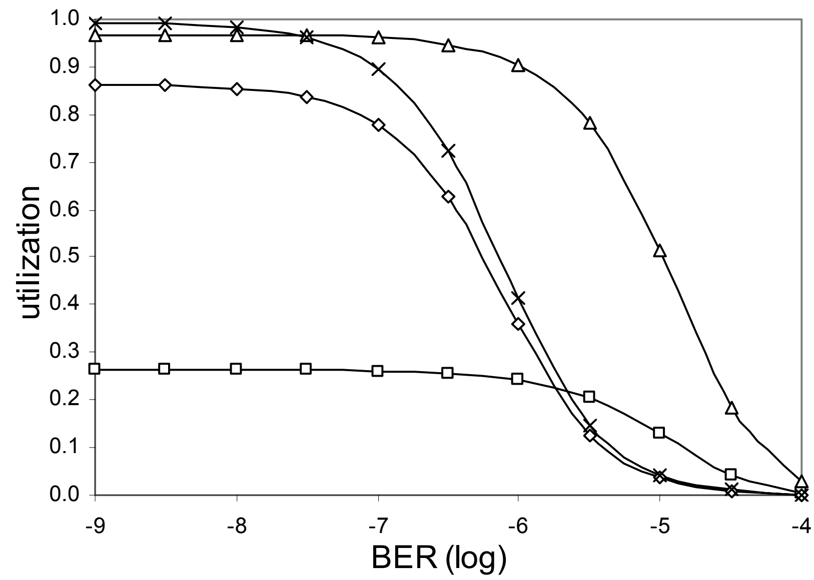


□ *C=115.2 Kbit/s, W_{max}=7* ◇ *C=576 Kbit/s, W_{max}=7* △ *C=1.152 Mbit/s, W_{max}=7*
x *C=4 Mbit/s, W_{max}=7* ◆ *C=4 Mbit/s, W_{max}=127*

Figure 3.6 Utilization versus BER for t_{ta}=10ms, l=16Kbits, $t_{Fout}=t_{Imax}+2t_{ta}$

the remaining two factors for IrPHY data rate evolution. IrPHY ver. 1.0 Serial Infrared (SIR) specification [50] supported data rates up to 115.2 Kbit/s using standard serial hardware, IrPHY ver. 1.1 Fast Infrared (FIR) [51] extended data speed to 4Mbit/s and finally IrPHY ver. 1.3 Very Fast Infrared (VFIR) [53] specification added the 16Mbit/s link rate. Table 3.2 presents the data rates introduced by new specifications, the year a specification was introduced, specification's maximum window size, maximum window size that can be enforced for 16Kbit frames within T_{max} (denoted by *N*), specification's t_{ta} and the two factors that contribute to WTT. Table 3.2 reveals that although FIR introduced much higher speeds (up to 4Mbit/s), it did not change the maximum t_{ta} value allowed for FIR IrDA ports. As a result, time utilized on user data transmission dropped from 427.9 ms to 28.8 ms while time utilized on reversing link direction twice, was steady at 20 ms as the t_{ta} value was not changed [92]. As a result, 4Mbit/s IrDA links employing the maximum allowed t_{ta}=10ms spend 20ms for acknowledgments for every 28.8ms of data transmission! Fig. 3.6 plots utilization versus BER for SIR and FIR link rates with t_{ta}=10ms, W_{max}=7 and *l*=16Kbits. Utilization decreases with data rate increase as the link turn around frequency is increased. As a result a maximum utilization of 0.59 can be achieved for 4 Mbit/s links.

VFIR specification, along with introducing the higher 16Mbit/s rate, addressed the

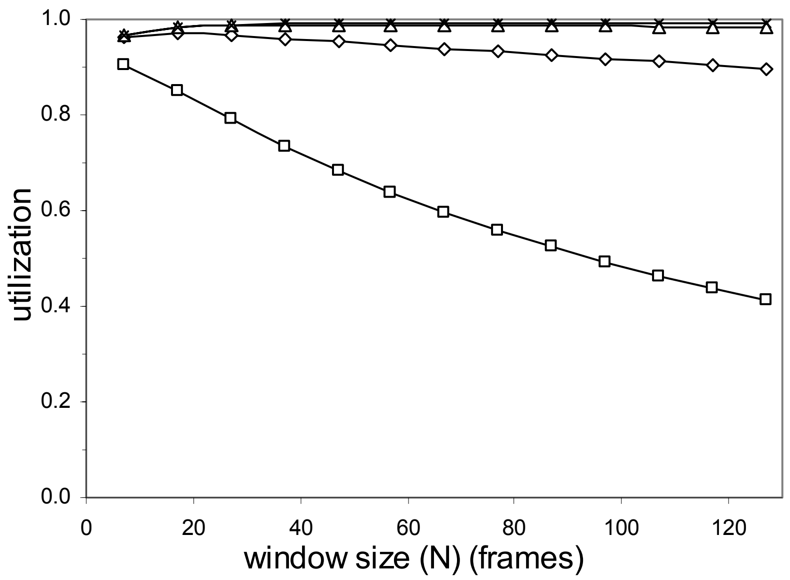


□ W_{max}=7, t_{ta}=10ms
◇ W_{max}=127, t_{ta}=10ms
△ W_{max}=7, t_{ta}=0.1ms
x W_{max}=127, t_{ta}=0.1ms

Figure 3.7 Utilization versus BER for C=16Mbit/s, l=16Kbits, $t_{Fout}=t_{Imax}+2t_{ta}$

problem by reducing t_{ta} to 0.1 ms and by optionally increasing window size to 127 frames for 16Mbit/s links [53]. 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. 3.6 plots utilization versus link BER for 4 Mbit/s links with t_{ta}=10ms, l=16Kbits and a window size of 127 frames. Utilization significantly increases with the 127 window size employment and reaches the acceptable value of 0.96 at low BER.

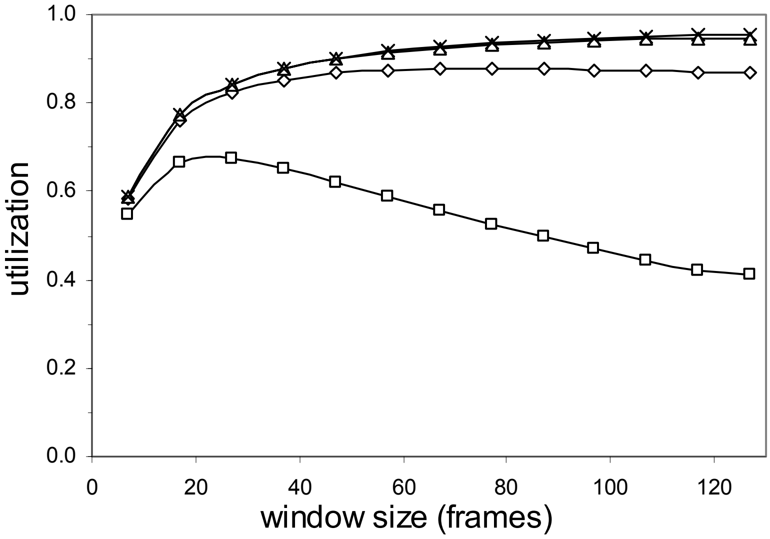
Fig. 3.7 plots utilization versus link BER. It examines the effect in utilization of reducing t_{ta} and/or increasing window size for a 16 Mbit/s link. Utilization for t_{ta}=10ms and W_{max}=7 shows that the increased turnaround frequency results in poor performance. Reducing acknowledgement time portion by only increasing window size (t_{ta}=10ms and W_{max}=127) results in a significant increase but yet a questionable performance. By reducing only t_{ta} (t_{ta}=0.1ms and W_{max}=7) an excellent performance is observed. Taking further advantage of the optional window size increase (t_{ta}=0.1 ms and W_{max}=127) results a slightly better performance for low BER but renders the link vulnerable to BER increase as it requires a link BER of 10^{-8} to achieve an excellent performance as opposed to a 10^{-7} BER requirement for W_{max}=7. As a conclusion, t_{ta} adjustment is a necessity while the effectiveness of window size increase is debatable.



□ $p_b=10^{-6}$
◇ $p_b=10^{-7}$
△ $p_b=10^{-8}$
x $p_b=10^{-9}$

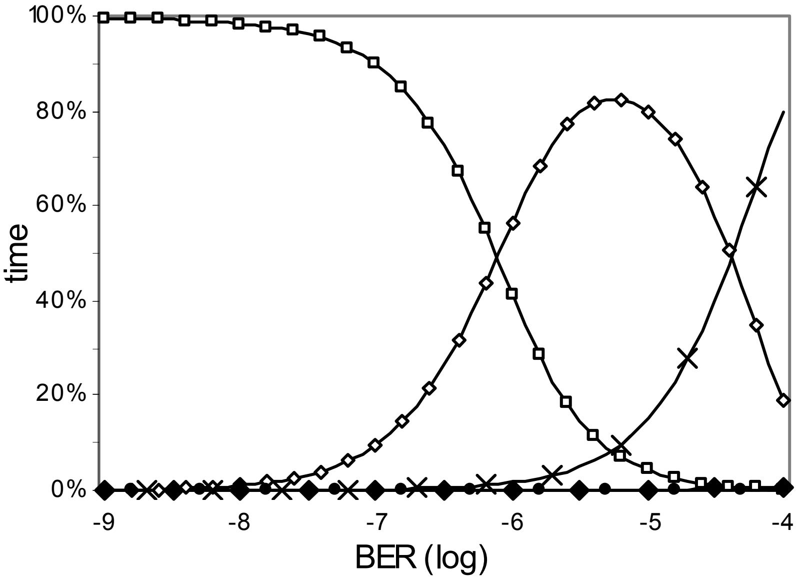
Figure 3.8 Utilization versus window size for C=16Mbit/s, t_{ta}=0.1ms, l=16Kbits, $t_{Fout}=t_{Imax}+2t_{ta}$

Fig. 3.8 plots utilization versus window size for different link BERs for 16Mbit/s links with t_{ta}=0.1 ms. Window size increase results in slight utilization increase for low BERs and significant decrease for high BERs. Fig. 3.9 plots utilization versus window size for 4Mbit/s links with t_{ta}=10ms. A much different behavior is observed due to the large link turnaround time value as related to data rate. A significant utilization increase with window size increase for low BER is observed as the link turnaround frequency is decreased. This also applies for high BER (10^{-6}) but when window size becomes very large, a utilization decrease is observed caused by the increased number of retransmitted frames following an error frame in a window transmission. Fig. 3.10 shows the % time consumed for different IrLAP tasks for a 16Mbit/s link with W_{max}=127 and t_{ta}=0.1 ms. It reveals that for high window size values (W_{max}=127), the key factor that reduces utilization for a wide range of BER (from 10^{-8} to 10^{-4}) is the retransmission of correctly received out of sequence frames. This is a limitation of the IrDA IrLAP protocol when non-optimum window size is used, especially for high BER [18]. As a conclusion, high window size employment increases utilization by reducing the link turn around frequency. The price we pay for using high window sizes is that utilization becomes sensitive to an increase in BER.



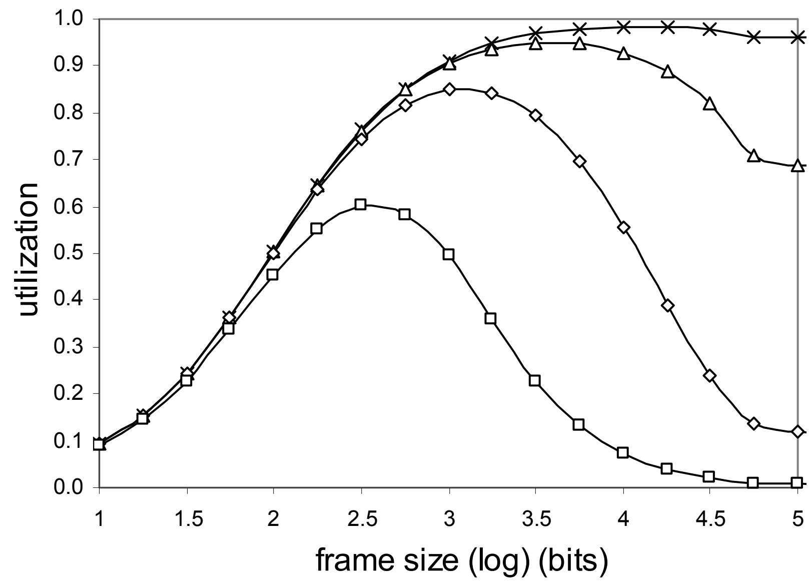
□ $p_b=10^{-6}$
◇ $p_b=10^{-7}$
△ $p_b=10^{-8}$
x $p_b=10^{-9}$

Figure 3.9 Utilization versus window size for C=4Mbit/s, t_{ta}*=10ms, l=16Kbits,* $t_{Fout}=t_{Imax}+2t_{ta}$



□ *useful data transmission (utilization)*
◇ *retransmission of correctly received out of sequence frames*
x *retransmission of error frames*
◆ t_{Fout} *timer expiration*
● *reversing link direction (hardware latency)*

Figure 3.10 Time allocation of various IrLAP tasks versus BER, C=16Mbit/s, l=16Kbits, W_{max}*=127 frames,* t_{ta}*=0.1ms,* $t_{Fout}=t_{Imax}+2t_{ta}$



□ $p_b=10^{-5}$
◇ $p_b=10^{-6}$
△ $p_b=10^{-7}$
x $p_b=10^{-8}$

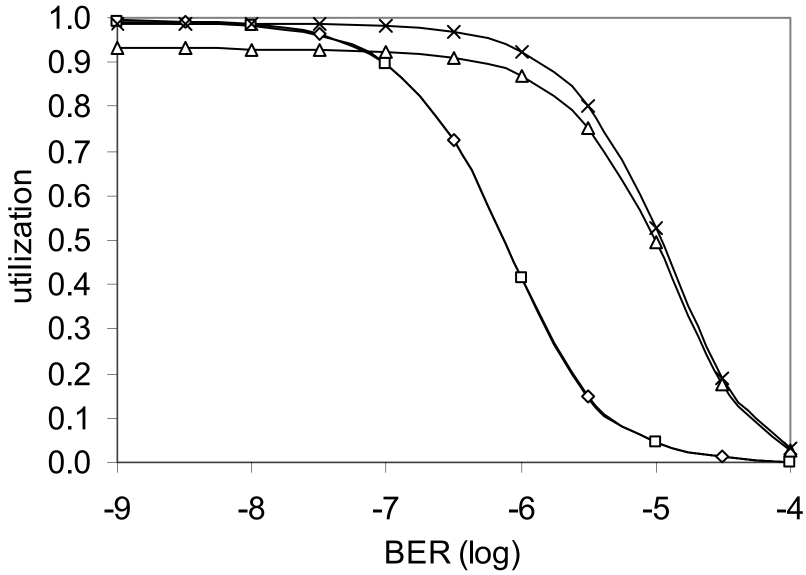
Figure 3.11 Utilization versus frame size for C=16Mbit/s, $t_{ta}=0.1ms, W_{max}=127$ *frames,* $t_{Fout}=t_{Imax}+2t_{ta}$

Fig. 3.11 plots utilization 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 implemented at high BER for maximum utilization. Thus, optimum window size and frame size parameters are of great importance for IrLAP performance.

3.7 IrLAP performance for future high data rates

IrDA is expected to develop new IrPHY specifications that will support higher data rates to meet user needs for faster information transfers [47][17]. This section examines how well the IrLAP protocol fares with predicted future increases of IrPHY data rates if optimum window and frame size values are not implemented. It focuses on whether the new IrPHY specification should decrease or not the maximum t_{ta} value defined in the current IrPHY ver. 1.3 VFIR specification (t_{ta}=0.1ms) [53] as related to the window size that IrLAP utilizes for efficient data transfers.

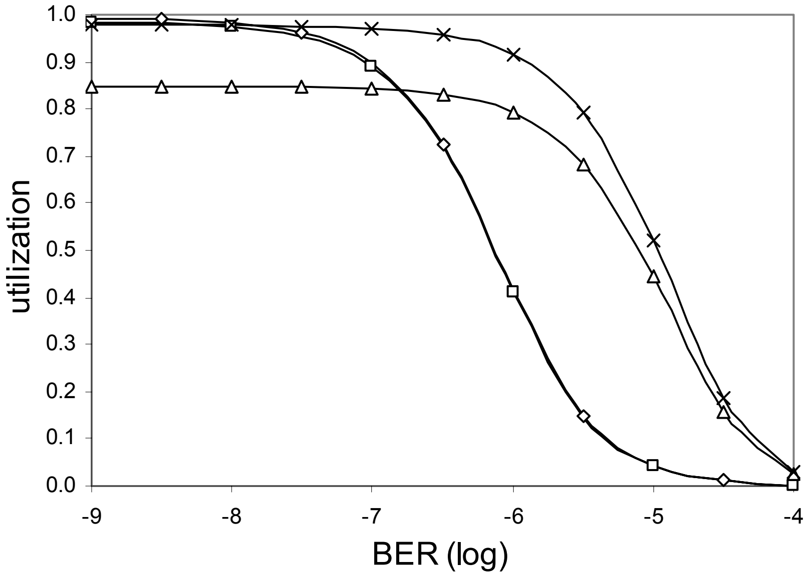
Fig. 3.12 plots utilization versus BER for C=40 Mbit/s and different window size and t_{ta} values. It shows that for W_{max}=127 frames, reducing t_{ta} to 0.01ms is not beneficial because no utilization increase is observed. For W_{max}=127 frames, IrLAP performance is



□ W_{max}=127, t_{ta}=0.1ms
◇ W_{max}=127, t_{ta}=0.01ms
△ W_{max}=7, t_{ta}=0.1ms
x W_{max}=7, t_{ta}=0.01ms

Figure 3.12 Utilization versus BER for C=40Mbit/s, l=16Kbits, $t_{Fout}=t_{Imax}+2t_{ta}$

vulnerable to BER increase. If IrLAP utilizes a window size of 7 frames (W_{max}=7), reducing t_{ta} to 0.01 results in utilization improvement for low BER. In addition, the low window size value renders the link more robust to BER increase. Fig. 3.13 plots the same results for C=100Mbit/s. Reducing t_{ta} to 0.01 ms is not again beneficial for W_{max}=127. However, if W_{max}=7 frames, reducing t_{ta} to 0.01ms highly improves utilization for low BER. As a conclusion, the t_{ta} value defined in the future IrPHY specification should not be reduced if future high speed (40 Mbit/s or 100 Mbit/s) IrDA links are expected to operate in good quality links that have a low BER. If it is desired that the future high speed links should be more robust to BER increase, a lower t_{ta} of 0.01 ms should be defined and the IrLAP should utilize low (or optimum) window sizes in low quality infrared links.



□ W_{max}=127, t_{ta}=0.1ms
◇ W_{max}=127, t_{ta}=0.01ms
△ W_{max}=7, t_{ta}=0.1ms
x W_{max}=7, t_{ta}=0.01ms

Figure 3.13 Utilization versus BER for C=100Mbit/s, l=16Kbits, $t_{Fout}=t_{Imax}+2t_{ta}$