CHAPTER 7

Advanced Infrared Link Control Layer

In the previous chapter, AIr performance was evaluated for error free transmissions; the frame error probability f_e was always zero. In addition, no Repetition Rate implementation was considered (RR=1). Only empty slots, collisions, reservation control frames and frame overheads could result in utilization degradation. In this chapter, the error free results will be re-examined in the light of realistic link error rate conditions due to noise.

Frame errors may result in significant delays and utilization degradation. In addition, retransmission schemes utilize acknowledgments that affect utilization. This chapter presents a complete AIr LC performance evaluation by considering delays arising from collision avoidance procedures, retransmission schemes and RR-coding. It focuses on the reliable information transfer procedures of the LC layer. The evaluation considers medium access delays by employing the analytical model presented in the previous chapter. It also considers acknowledgement and retransmission delays by developing analytical models for the AIr retransmission schemes. RR-coding delays are included using an analytical model that evaluates frame error rate for the receiver's signal to noise ratio and the frame RR value.

AIr protocol always employs an Automatic Repeat Request (ARQ) retransmission scheme to ensure correct reception of the transmitted information. AIr implements several ARQ schemes. The AIr MAC [45] sub-layer may:

a) not implement any retransmission scheme and not transmit any acknowledgments (DATA frames),
b) implement frame level acknowledgments (ADATA frames) or
c) sequence data frames and implement acknowledgments for a window of frames (SDATA frames).

The AIr LC sub-layer [43] implements a Go-Back-N (GBN) ARQ retransmission scheme to guarantee correct data reception. However, LC may rely on MAC retransmission procedures to guarantee that the transmitted data are successfully received by the remote device [43]. In this case, the remote device is not polled at the LC layer and no LC layer acknowledgments are transmitted. This chapter presents analytical models for these ARQ schemes and employs the models to study AIr performance under different channel error conditions and for various parameters such as window size, frame length and turn around delays.

AIr may also employ Repetition Rate (RR) coding to cope with transmission errors. For stations far away from the transmitter with a low signal to noise ratio (SNR), a 4-PPM symbol is repeated RR times in order to increase the symbol capture probability at the receiver. RR is a way of adapting link rate to channel conditions. RR coding is not a reliable information transfer scheme but significantly reduces error rate. An analytical model that evaluates frame error rate as a function of RR and signal to noise ratio is presented. The analytical model is employed to study the effectiveness of the RR coding to channel utilization for the proposed ARQ schemes.

This chapter outline is as follows. Section 7.1 defines the proposed ARQ protocols that may be employed by AIr applications to successfully transmit data using the infrared medium. Section 7.2 develops analytical models that calculate the utilization of the proposed protocols and section 7.3 employs the analytical models to compare protocol performance for various link parameter values when RR coding is not implemented. Section 7.4 presents an analytical model that calculates frame error rate for a station's SNR when RR coding is implemented. Finally, section 7.5 studies the performance of the proposed ARQ protocols when RR coding is implemented and the suitable RR value for a station's SNR is used.

7.1 Protocol definition

7.1.1 FLACK and FLACK-M definition

AIr MAC layer may employ a Stop-and-Wait (SW) ARQ scheme or a GBN ARQ scheme or no ARQ scheme at all. SW ARQ scheme utilizes the Reserved transfer mode with acknowledgment; GBN ARQ scheme utilizes the Reserved transfer mode with sequenced data and if no ARQ scheme is employed, the Reserved transfer mode with DATA frame is utilized. The transfer modes are explained in section 5.3. When the Reserved transfer mode with DATA frame is utilized at the MAC layer, a MAC layer transmission indication to the upper layer means that the data are transmitted and not that the data are correctly received [45]. When an ARQ scheme is implemented at the MAC layer, a MAC layer transmission indication to the upper layer means that the data are correctly received by the remote station.

Frame level acknowledgment (FLACK) protocol utilizes the GBN ARQ scheme at the LC layer and the SW ARQ scheme at the MAC layer (Fig. 7.1). FLACK is a two-level ARQ scheme as it separately acknowledges every frame at the MAC layer and every window of frames at the LC layer [72]. However, the AIr LC specification [43] defines that the LC layer may rely on the MAC reliable information delivery schemes to guarantee that the transmitted data frames are correctly received. In this case, the LC layer employs its GBN ARQ scheme only when no ARQ scheme is utilized at the MAC layer; no ARQ scheme is employed at the LC layer otherwise. Frame level acknowledgment MAC (FLACK-M) protocol employs the SW ARQ scheme at the MAC layer and no ARQ scheme at the LC layer (Fig. 7.2) [93]. FLACK and FLACK-M protocols can not take advantage of the sliding window mechanism but they can quickly adapt the implemented RR to channel conditions by means of the RR recommendations provided by the receiver's MAC ACK frames.

Figures 7.1 and 7.2 portray FLACK and FLACK-M operation respectively for a window size of 4. The transmitter captures the channel, sends an ADATA frame and waits for the responding MAC ACK frame. If the ADATA frame is received correctly, the receiver waits a turn around time (TAT) period to allow the transmitter's circuitry to recover and responds with an ACK frame. When the ACK frame is received, indicating successful reception of the ADATA frame, the transmitter proceeds with the transmission of the next frame. Assuming frame 3 is lost (Figures 7.1 and 7.2), the timer for the responding MAC ACK frame expires. The considered MAC ACK time out period equals the time required for receiving the MAC ACK frame. The transmitter terminates current reservation by means of an EOB frame and contends again for medium access in an effort to transmit the remaining frames during its next successful reservation. As FLACK and FLACK-M protocols can not use the sliding window mechanism, the next reservation contains only frames 3 and 4 and not a full window of frames in both cases. If FLACK-M protocol is implemented (Fig. 7.2), the transmitter does not set the Poll/Final (P/F) bit in the MGMT field of the last ADATA frame it transmits (frame 4) because FLACK-M does not employ a GBN ARQ scheme at the LC layer. If FLACK protocol is implemented (Fig. 7.1), the transmitter sets the P/F bit in the last ADATA frame it transmits and the receiver reserves the medium and responds

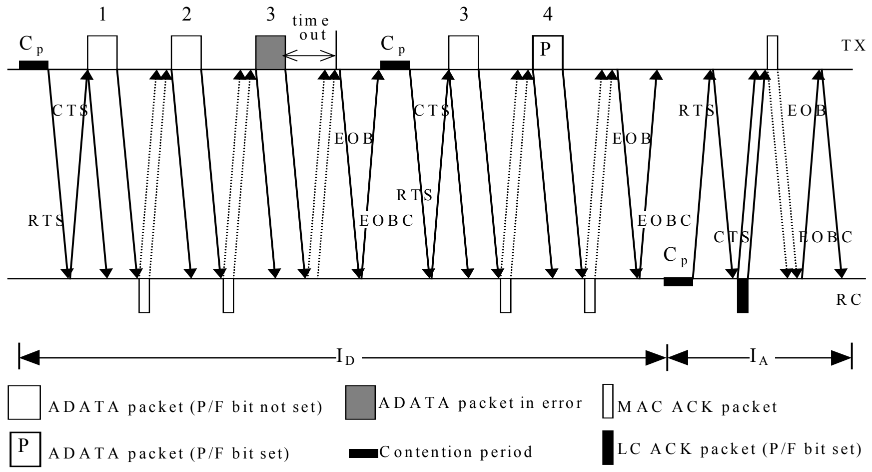


Figure 7.1 FLACK protocol (SW ARQ at the MAC layer and GBN at the LC layer)

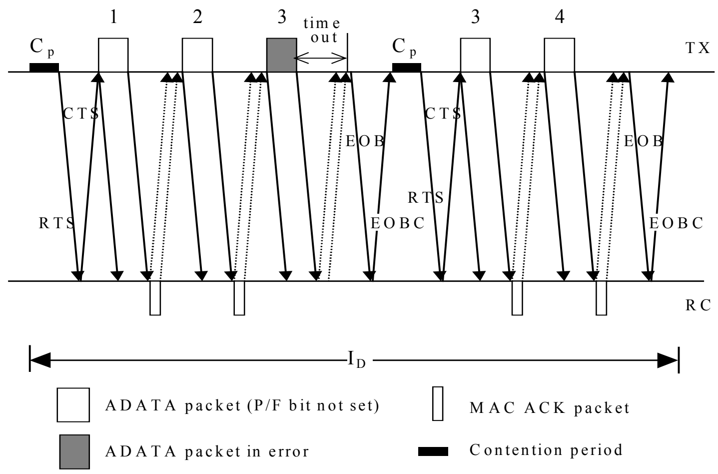


Figure 7.2 FLACK-M protocol (SW ARQ at the MAC layer and no ARQ scheme at the LC layer)

with an LC receive ready acknowledgment (LC ACK) frame. If the last ADATA frame carrying the P/F bit is lost, the transmitter immediately realizes the P/F loss by a time out expiration for the MAC ACK frame and contends again in order to retransmit the last ADATA frame.

7.1.2 NoFLACK and NoFLACK-ACK definition

An alternative is for the LC layer to employ its GBN ARQ scheme and to disable the MAC layer ARQ schemes [43]. LC GBN scheme sets the P/F bit in a transmitted frame to pass transmission control. AIr LC specification defines that the P/F bit may be set in a data or in an LC receive ready acknowledgment (LC ACK) frame. LC ACK frames are transmitted as MAC data frames with no information data. Thus, two

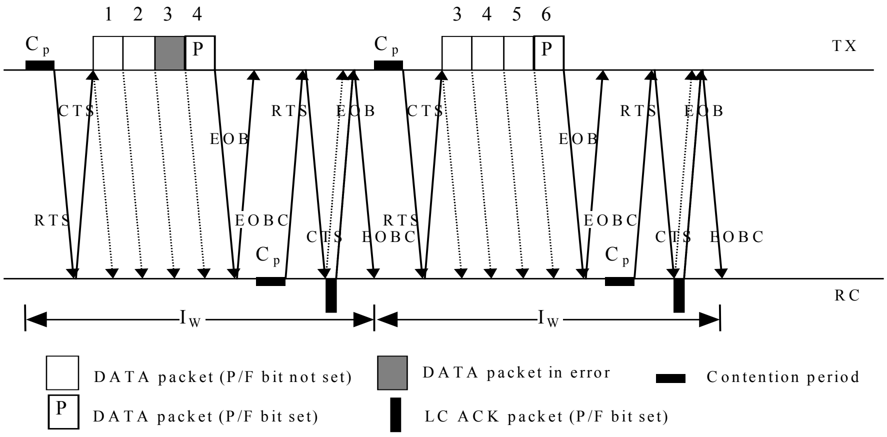


Figure 7.3 NoFLACK protocol (no ARQ at the MAC layer, GBN at the LC layer and P/F bit in DATA frame)

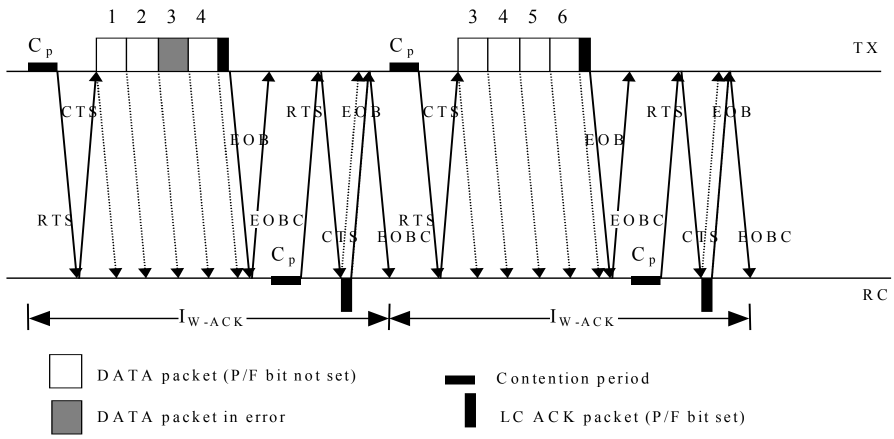


Figure 7.4 NoFLACK-ACK protocol (no ARQ at the MAC layer, GBN at the LC layer and P/F bit in ACK frame)

different operation modes are considered for the LC GBN ARQ scheme. The first always sets the P/F bit in the last DATA frame in a window transmission (Fig. 7.3); the second always sets the P/F bit in a special LC ACK frame that follows the last DATA frame in a window transmission (Fig. 7.4). No frame level acknowledgment (NoFLACK) protocol utilizes the GBN ARQ scheme at the LC layer, no ARQ scheme at the MAC layer and utilizes DATA frames to carry the P/F bit to the receiver (Fig. 7.3). No frame level acknowledgment protocol utilizing LC ACK frames (NoFLACK-ACK) protocol uses the GBN ARQ scheme at the LC layer, no ARQ scheme at the MAC layer and always utilizes LC ACK frames to carry the P/F bit to the receiver (Fig. 7.4) [93].

NoFLACK protocol sets the P/F bit in the last DATA frame in a window transmission. The receiver acknowledges in-sequence correctly received frames and returns transmission control by setting the P/F bit in the responding LC ACK frame. When DATA frames contain a significant amount of information data and link error rate is high, the DATA frame carrying the P/F bit may be lost. In the case of a P/F bit loss, the receiver fails to acknowledge correctly received DATA frames because it assumes that the transmitter wishes to send more DATA frames before soliciting a response. The situation is resolved by a transmitter's LC layer time out expiration, following which the transmitter sends an LC ACK frame with the P/F bit set. The receiver responds with an LC ACK frame with the P/F bit set, acknowledging correctly received frames and returning transmission control. NoFLACK-ACK protocol reduces the P/F bit loss probability by not setting the P/F bit in the last DATA frame in a window transmission and by transmitting a new (and much smaller) LC ACK frame carrying the P/F bit which follows the last DATA frame in a window transmission. NoFLACK-ACK protocol reduces the P/F bit loss probability at the expense of transmitting a new LC ACK frame.

NoFLACK and NoFLACK-ACK protocols can use the sliding window mechanism but they can not quickly adapt their RR value to channel conditions because the receiver can only recommend new RR values by using the RR* field of the EOBC frame that terminates a reservation.

Figures 7.3 and 7.4 portray NoFLACK and NoFLACK-ACK protocol operation respectively. The transmitter transmits all frames upon gaining access to the infrared medium. As explained earlier, NoFLACK (Fig. 7.3) sets the P/F bit in the last DATA frame it transmits (frame 4 and 6); NoFLACK-ACK (Fig. 7.4) does not and sends a new LC ACK frame with the P/F bit set. Upon receiving a frame with the P/F bit set, the receiver, in both cases, responds with an LC ACK frame informing the transmitter of the in sequence correctly received frames. The LC ACK frame has the P/F bit set returning transmission control to the transmitter. If all frames are correctly received, the transmitter sends the next window of frames. Otherwise, it repeats the erred frame, retransmits all frames that followed the erred frame during the previous window transmission and, by taking advantage of the sliding window mechanism, the transmitter also sends new frames to form a complete window transmission. If again frame 3 is lost (Fig. 7.3 & 7.4), both protocols retransmit frames 3 and 4 and transmit new frames 5

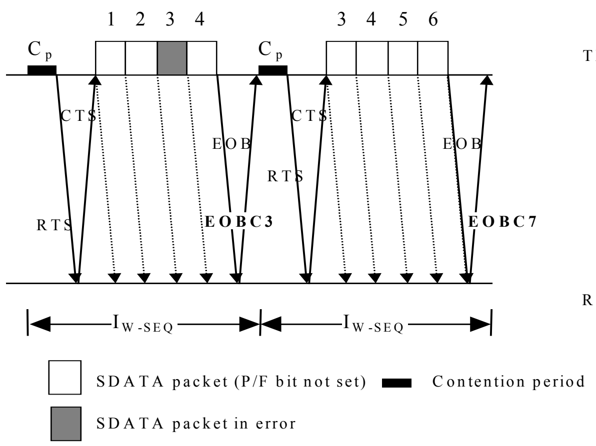


Figure 7.5 SEQ-NoFLACK protocol (GBN at the MAC layer and no ARQ scheme at the LC layer)

and 6 to form a complete window transmission. If the frame carrying the P/F bit is lost, the information transfer procedure is halted. The situation is resolved by a transmitter's LC time out expiration. The transmitter then sends an LC ACK frame with the P/F bit set forcing the receiver to acknowledge correctly received frames. Current analysis assumes that LC ACK frames are very small and are always correctly received.

7.1.3 SEQ-NoFLACK definition

Another alternative for the LC layer is to instruct the MAC layer to sequence data frames by employing the Reserved transfer mode with sequenced data. In this case, the EOBC control frame that terminates the reservation contains a sequence number that informs the transmitter of the next frame sequence number expected. This sequence number acknowledges in sequence correctly received frames, as described in section 5.3.2.3, and allows AIr MAC to implement a GBN ARQ retransmission scheme. Sequential no frame level acknowledgment (SEQ-NoFLACK) protocol implements the GBN ARQ scheme at the MAC layer and no ARQ scheme at the LC layer. SEQ-NoFLACK protocol incurs the least overhead because no special LC ACK or MAC ACK frames are transmitted and correctly received frames are acknowledged using the EOBC control frame that terminates a successful reservation. The SEQ-NoFLACK protocol can use the sliding window mechanism but it can not quickly adapt the implemented RR to channel conditions because the receiver can only recommend suitable RR values by using the RR* field of the EOBC frame.

Fig. 7.5 depicts SEQ-NoFLACK protocol operation. The transmitter sends a window of SDATA frames after a successful RTS/CTS frame exchange. The SDATA frames contain frame sequence numbers. As no ARQ scheme is implemented at the LC layer, the P/F bit in the last SDATA frame is not set. However, the receiver informs the transmitter of the correctly received frames by using the Seq-R field of the EOBC control frame. If all frames are received successfully, the transmitter proceeds with the next window transmission. If again frame 3 is lost (Fig. 7.5), the transmitter contends again in order to retransmit frames 3 and 4. SEQ-NoFLACK protocol can use the sliding window mechanism and therefore new frames 5 and 6 are transmitted to form a complete window transmission during the next successful reservation.

7.2. Protocol analysis

Current analysis considers a LAN of n transmitting stations operating in saturation conditions, i.e. all n stations always have a window of frames ready for transmission. It is assumed that the LC ACK frames are small enough to be always received error free. The analysis considers the preparation time of a data frame and assumes that the processing time of a received data or ACK frame is smaller than the minimum turn around time (TAT) and can overlap with the TAT delay. Thus, no additional received frame processing time is calculated. The receiver processes the received frame and then waits until a total of TAT period is reached before transmitting the suitable response. It is also assumed that the processing time of a received frame can also overlap with the reception of the next frame and it is not additive.

7.2.1 FLACK utilization

The FLACK protocol utilization can be found by evaluating the number of reservations required to successfully transmit a window of w frames. For frame error rate f_e, the probability $P_{s/i}$ that i reservations are required to successfully transmit a window of frames is given by [76]

$$P_{s/i} = C_{i-1}^{w+i-2}(1-f_e)^w f_e^{i-1} \tag{7.1}$$

where

$$C_{i-1}^{w+i-2} = \frac{(w+i-2)!}{(i-1)!\,(w-1)!} \tag{7.2}$$

The transmission time of w frames if i reservations are required is given by

$$T_D(i) = i(C_p + D) + (w + i - 1)(t + F_A + p_1 + E) \tag{7.3}$$

where F_A is the transmission time of ADATA frame overhead (PA, RH, CRC etc.), E is the time required for a MAC acknowledgement and consists of the MAC ACK frame transmission time and of the TAT delays associated with this MAC ACK transmission and C_p, D, t and p_1 are as defined in the previous chapter. C_p is the average contention period (including empty and collision slots) for a successful reservation and is given by eq. (6.28), D is the reservation overhead that includes the transmission time of the RTS, CTS, EOB and EOBC frames and the TAT delays that follow these frames and equals 1.74 msec, t is the payload data transmission time and p_1 is the preparation time of a data frame. The value of t is given by

$$t = \frac{RR\, l}{C} \tag{7.4}$$

where RR, C and l are as defined in the previous chapter. RR is the Repetition Rate, C is the link base rate and l is the payload data length. The value of F_A is given by

$$F_A = T_{RH} + \frac{RR\, l'_A}{C} \tag{7.5}$$

where l'_A is the length of the MBR overhead of an ADATA frame and T_{RH} is as defined in section 5.2. T_{RH} is the transmission time of a frame with no MBR field. According to Fig. 5.3, l'_A =72 bits and section 5.2 evaluates that T_{RH}=232 μsec.

The transmission time, I_D, for a complete w frame transmission can be calculated by

$$I_D = \sum_{i=1}^{\infty} P_{s/i} T_D(i) \tag{7.6}$$

As LC ACK frames are always transmitted error free, the transmission time of the LC ACK frame is given by

$$I_A = (C_p + D) + (t_A^{ack} + p_1 + E) \tag{7.7}$$

where t_A^{ack} is the LC ACK frame transmission time when ADATA frames are utilized and the other parameters are the same. E in eq. (7.7) stands for the time needed to acknowledge the LC ACK frame at the MAC layer. As the LC ACK frame does not contain payload data,

$$t_A^{ack} = F_A \tag{7.8}$$

The FLACK protocol utilization can now be derived as

$$U_{FLACK} = \frac{1}{RR} \frac{wt}{I_D + I_A} \tag{7.9}$$

7.2.2 FLACK-M utilization

The same analytical model can be applied to the FLACK-M protocol. Considering that the FLACK-M does not implement the GBN ARQ scheme at the LC layer and therefore no LC ACK frames are transmitted, the FLACK-M utilization can be evaluated by

$$U_{FLACK-M} = \frac{1}{RR} \frac{wt}{I_D} \tag{7.10}$$

where I_D is given by eq. (7.6).

7.2.3 NoFLACK-ACK utilization

As the NoFLACK-ACK protocol only implements the GBN ARQ scheme at the LC layer, its utilization can be found with the help of the analysis presented in section 3.4 for GBN protocols

$$U_{NoFLACK-ACK} = \frac{t}{RR} \frac{(1-f_e)}{f_e} \cdot \frac{\left(1-(1-f_e)^w\right)}{I_{W-ACK}} \tag{7.11}$$

where $I_{W\text{-}ACK}$, the window transmission time, is given by

$$I_{W-ACK} = 2(C_p + D) + w(t + F_D + p_1) + 2(p_1 + t_D^{ack}) \tag{7.12}$$

where F_D is the transmission time of DATA frame overhead, t_D^{ack} is the LC ACK frame transmission time when DATA frames are utilized and the other parameters are as defined for the FLACK protocol. The value of F_D is given by

$$F_D = T_{RH} + \frac{RR\, l_D^{'}}{C} \tag{7.13}$$

where $l_D^{'}$ is the length of the MBR overhead bits of a DATA frame and the other parameters are the same. According to Fig. 5.3, $l_D^{'}$ =72 bits. As the LC ACK frame does not contain payload data,

$$t_D^{ack} = F_D \tag{7.14}$$

The window transmission time, $I_{W\text{-}ACK}$, does not consider the P/F bit loss delay because NoFLACK-ACK sets the P/F bit in LC ACK frames only and current model assumes that LC ACK frames are small enough to be always received error free.

7.2.4 NoFLACK utilization

In the NoFLACK protocol, the information transfer procedure is halted when the P/F bit is lost and is restarted again when the LC timer expires. If one station is transmitting in the infrared LAN, this situation clearly results in link idle time and utilization degradation. However, if many stations are transmitting in the LAN, the utilization may not be significantly decreased if the probability that all transmitting stations suffer from P/F bit loss simultaneously is very low. If a few stations are transmitting in the LAN, utilization is decreased because the medium is idle when all stations lose the P/F bit simultaneously.

It is difficult and worthless to develop an analytical model that evaluates NoFLACK utilization as a function of the number of stations in the LAN. The reason is that when the P/F bit is lost, the transmitting station does not contend for medium access. As a result, the number of stations competing for medium access is not fixed and a new model that evaluates the average contention period (C_p) for a LAN with no fixed number stations is needed. However, the lower and upper limits of NoFLACK utilization can be evaluated for links with transmission errors. These limits are sufficient for the protocol comparison performed in this work.

The lower limit, $NoFLACK_1$, refers to the NoFLACK protocol scenario with only one transmitting station in the LAN. In this case, the infrared medium is idle for the entire LC time out period when a P/F bit is lost. The upper limit, $NoFLACK_N$, refers to NoFLACK protocol scenario with a significant (or infinite) number of transmitting stations. In this case, the infrared medium is equally utilized by the remaining stations in the case of one (or more) P/F bit loss. When one or more stations temporarily stop contending for medium access, the LAN utilization is not decreased but the utilization of every transmitting individual station is temporarily increased. Thus, all real life network scenarios implementing NoFLACK protocol will achieve a LAN utilization with an upper limit of the $NoFLACK_N$ utilization and a lower limit of the $NoFLACK_1$ utilization.

As NoFLACK implements only the GBN ARQ scheme at the LC layer, $NoFLACK_1$ utilization is given by

$$U_{NoFLACK_1} = \frac{t}{RR} \cdot \frac{(1-f_e)}{f_e} \cdot \frac{\left(1-(1-f_e)^w\right)}{I_{W-1}} \tag{7.15}$$

where I_{w-1} is the average window transmission time and is given by

$$I_{W-1} = 2(C_p + D) + w(t + F_D + p_1) + (p_1 + t_D^{ack}) + f_e(T_t + C_p + D + p_1 + t_D^{ack}) \quad (7.16)$$

where T_t is the LC layer time out period and the other parameters are as defined for the NoFLACK-ACK protocol.

If the considered LAN has a significant number of transmitting stations and the infrared medium is always fully utilized during LC time out periods, the utilization is given by

$$U_{NoFLACK_N} = \frac{t}{RR} \cdot \frac{(1-f_e)}{f_e} \cdot \frac{\left(1-(1-f_e)^w\right)}{I_{W-N}} \quad (7.17)$$

and I_{W-N} is given by

$$I_{W-N} = 2(C_p + D) + w(t + F_D + p_1) + (p_1 + t_D^{ack}) + f_e(C_p + D + p_1 + t_D^{ack}) \quad (7.18)$$

7.2.5 SEQ-NoFLACK utilization

The utilization of SEQ-NoFLACK protocol can be evaluated by the analysis of the GBN protocols

$$U_{SEQ-NoFLACK} = \frac{t}{RR} \cdot \frac{(1-f_e)}{f_e} \cdot \frac{\left(1-(1-f_e)^w\right)}{I_{W-SEQ}} \quad (7.19)$$

where I_{W-SEQ}, the window transmission time, is given by

$$I_{W-SEQ} = (C_p + D) + w(t + F_S + p_1) \quad (7.20)$$

and F_S is (as defined in the previous chapter) the transmission time of SDATA frame overhead and the other parameters are the same. The value of F_S is given by

$$F_S = T_{RH} + \frac{RR\, l_S^{'}}{C} \quad (7.21)$$

where $l_S^{'}$ is the length of the MBR overhead of a SDATA frame and the other parameters are the same. According to Fig. 5.3, $l_S^{'}$ =80 bits.

As the utilization analysis presented in the previous chapter for error free channels uses SDATA frames, it refers to SEQ-NoFLACK protocol analysis for f_e=0. If $f_e \to 0$, eq. (7.19) reduces to

$$U_{SEQ-NoFLACK} = \frac{wt}{RR\ I_{W-SEQ}} \quad (7.22)$$

From eq. (7.20) and eq. (6.23), we can deduce that

$$I_{W-SEQ} = C_p + T_s \quad (7.23)$$

By substituting C_p from eq. (6.28)

$$I_{W-SEQ} = \frac{1 - P_{tr} P_s}{P_{tr} P_s} \sigma + T_s \quad (7.24)$$

and from eq. (7.24) and eq. (7.22)

$$U_{SEQ-NoFLACK} = \frac{1}{RR} \cdot \frac{wt}{\frac{1 - P_{tr} P_s}{P_{tr} P_s} \sigma + T_s} = \frac{1}{RR} \cdot \frac{P_{tr} P_s wt}{P_{tr} P_s T_s + \sigma - P_{tr} P_s \sigma} \quad (7.25)$$

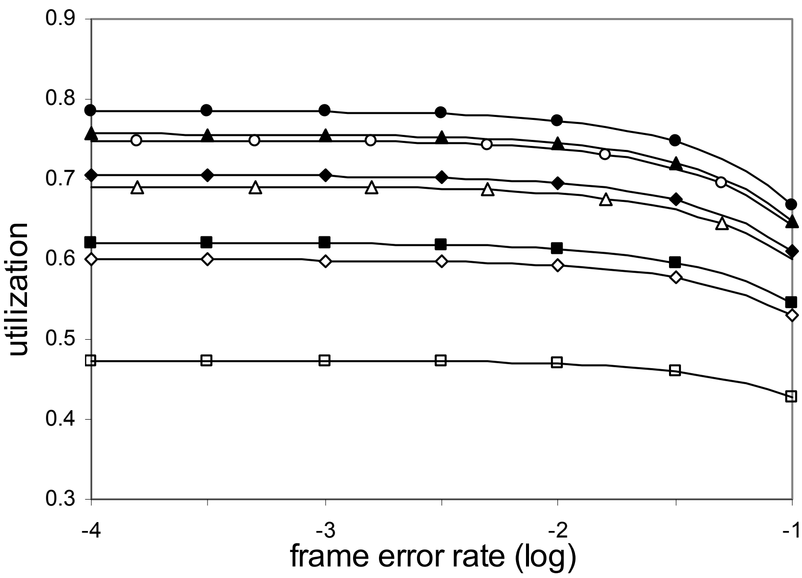
which is identical to eq. (6.22).

7.3. Performance comparison

Based on the analytical models presented in the previous section, protocol performance is compared under the assumption that no Repetition Rate (RR=1) coding is implemented. First, FLACK and FLACK-M protocols are compared and results indicate that FLACK-M offers a significantly higher utilization for the same link layer parameter values. Then, NoFLACK and NoFLACK-ACK protocols are compared and results indicate that NoFLACK-ACK is usually a better choice. Finally, NoFLACK-ACK, FLACK-M and SEQ-NoFLACK protocols are compared for different link layer parameter values.

7.3.1 FLACK versus FLACK-M

Fig. 7.6 compares FLACK and FLACK-M utilization versus frame error rate (FER) for various window size values. It shows that FLACK utilization is significantly lower than FLACK-M utilization for the same window size implementation. This result is explained by considering that FLACK is a two-way ARQ system. It implements an additional GBN ARQ scheme at the LC layer resulting in the transmission of additional LC ACK frames, additional RTS/CTS frame exchanges, contention periods, etc. Fig. 7.6 also shows that the FLACK protocol needs to double the implemented window size to reach a utilization figure close to FLACK-M protocol utilization. Utilization results produced for smaller *l* values indicate that this conclusion is always true and independent of the implemented frame size. Considering the conclusion derived in the previous chapter that the AIr protocol achieves high utilization only for high window size values and as the window size parameter is application dependent and thus not



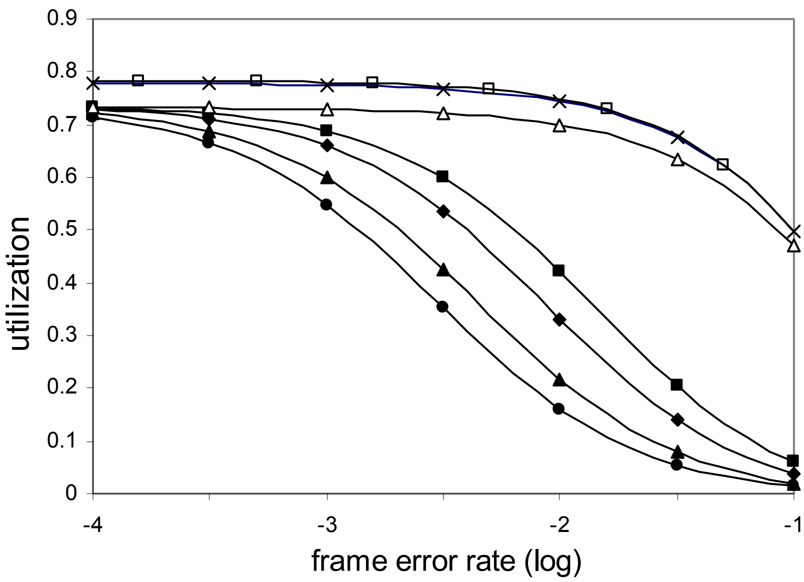
□ *FLACK, w=2 frames*
◇ *FLACK, w=4 frames*
△ *FLACK, w=8 frames*
○ *FLACK, w=16 frames*
■ *FLACK-M, w=2 frames*
◆ *FLACK-M, w=4 frames*
▲ *FLACK-M, w=8 frames*
● *FLACK-M, w=16 frames*

Figure 7.6 Utilization versus frame error rate for various w values, C=4Mbit/s, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations

directly controllable at the MAC layer, the FLACK-M protocol is a much better choice. Therefore, the FLACK-M protocol is chosen for the rest of this evaluation. As a conclusion, when the LC layer utilizes the MAC SW ARQ scheme, it should not employ its GBN ARQ scheme and should rely on MAC layer reliable data delivery techniques to guarantee that the transmitted information is actually received by the remote station. Implementation of an additional GBN ARQ scheme at the LC layer, which is very close to the MAC layer, results in significant delays and no significant benefits.

7.3.2 NoFLACK versus NoFLACK-ACK

Fig. 7.7 plots NoFLACK utilization versus FER for LANs with one (*n*=1) and ten (*n*=10) transmitting stations. $NoFLACK_1$ utilization is taken for *n*=1; $NoFLACK_N$ utilization is taken for *n*=10 assuming that the infrared medium is equally utilized during T_t time out periods for ten transmitting stations. As $NoFLACK_1$ and $NoFLACK_N$ utilization also serve as NoFLACK utilization lower and upper limit respectively, it is expected that NoFLACK utilization for LANs with more than one and less than ten



■ *NoFLACK*$_1$, T_t *=3 sec, n=1 station*
◆ *NoFLACK*$_1$, T_t *=5 sec, n=1 station*
▲ *NoFLACK*$_1$, T_t *=10 sec, n=1 station*
● *NoFLACK*$_1$, T_t *=15 sec, n=1 station*
□ *NoFLACK*$_N$, T_t *=3,5,10,15 sec, n=10 stations*
△ *NoFLACK-ACK*, T_t *=3,5,10,15 sec, n=1 station*
x *NoFLACK-ACK*, T_t *=3,5,10,15 sec, n=10 stations*

Figure 7.7 Utilization versus frame error rate for various T_t *values, w=8 frames, C=4Mbit/s, l=2Kbytes, W=8, m=62*

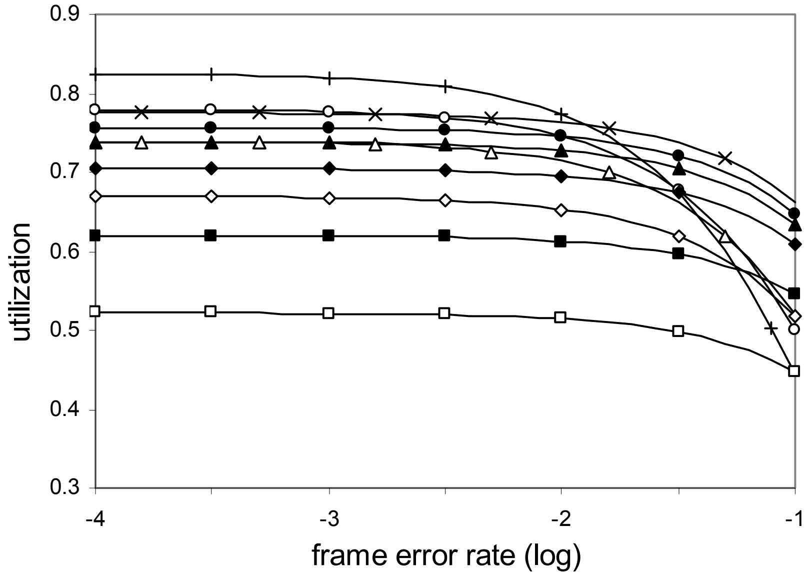
transmitting stations will fall between these limits. The reason is that the infrared medium will be partly utilized in the event of one or more P/F losses.

Fig. 7.7 shows that NoFLACK utilization degrades with FER increase and that it is more sensitive for n=1. In this case, utilization drop worsens with T_t value increase. The reason is that NoFLACK relies on the successful transmission of the last DATA frame to carry the P/F bit to the receiver. If the last DATA frame is lost, the station refrains from transmitting until the LC timer expires. As the NoFLACK$_1$ protocol scenario does not utilize these T_t periods, utilization degradation is increased for higher T_t values. NoFLACK$_N$ utilization is independent of T_t because the LC time out periods are fully utilized by the remaining stations.

Fig. 7.7 also plots NoFLACK-ACK utilization. NoFLACK-ACK utilization is always independent of T_t. The reason is that NoFLACK-ACK always sets the P/F bit in an LC ACK frame which is very small and has an extremely low (practically zero) error rate probability. Fig. 7.7 shows that for n=1, NoFLACK-ACK is a much better choice than $NoFLACK_1$ because it is robust to FER increase. For *n*=10, the NoFLACK-ACK protocol achieves a slightly lower performance (practically identical) than the $NoFLACK_N$ protocol scenario. The reason is that the additional LC ACK frame utilized by the NoFLACK-ACK protocol causes a small additional delay compared with other protocol delays such as contention periods, RTS/CTS exchanges etc. Considering that a) if NoFLACK protocol is implemented, the LAN utilization ranges from $NoFLACK_1$ utilization to $NoFLACK_N$ utilization, b) NoFLACK-ACK for *n*=1 performs better that $NoFLACK_1$, c) NoFLACK-ACK for large *n* reaches a practically identical to $NoFLACK_N$ performance, and d) NoFLACK does not in practice outperform NoFLACK-ACK and suffers from LC time out delays under certain conditions, we can conclude that the NoFLACK-ACK protocol is a much better choice than the NoFLACK protocol. Therefore, the NoFLACK-ACK protocol is selected for the rest of this evaluation. As a conclusion, the P/F bit should be set only in LC ACK frames if the MAC's SW ARQ scheme is not employed.

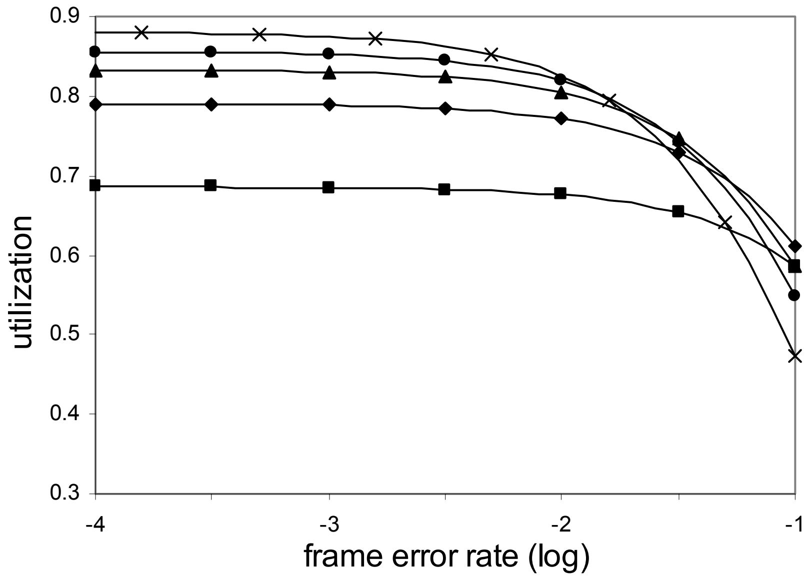
7.3.3 Comparison of FLACK-M, NoFLACK-ACK and SEQ-NoFLACK protocols

Fig. 7.8 compares FLACK-M and NoFLACK-ACK utilization for different window size values. It reveals that for low FER, the FLACK-M protocol performs better than the NoFLACK-ACK protocol for small window size values but the situation is reversed for high window size values. A 'critical' value of six frames exists where both protocols achieve the same utilization. Fig. 7.9 plots SEQ-NoFLACK utilization for the same parameter values. It shows that SEQ-NoFLACK protocol outperforms FLACK-M and NoFLACK-ACK protocols for all window sizes if FER is low. Figures 7.8 and 7.9 show that NoFLACK-ACK and SEQ-NoFLACK utilization decrease with FER increase but FLACK-M is more robust to FER increase. We can conclude that for low FER, the SEQ-NoFLACK protocol is the best choice and that the FLACK-M protocol is preferable to the NoFLACK-ACK protocol for window transmissions consisting of less than 6 frames; NoFLACK-ACK is better otherwise.



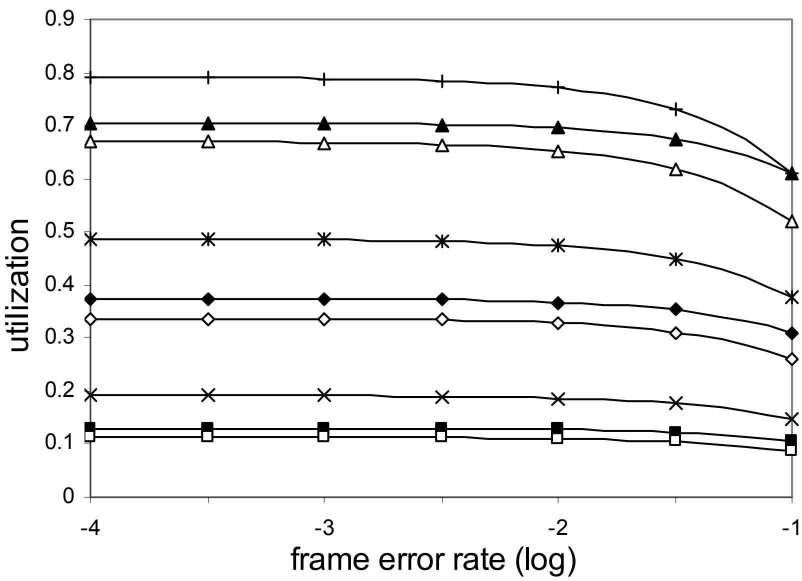
□ *NoFLACK-ACK, w=2 frames* ■ *FLACK-M, w=2 frames*
◇ *NoFLACK-ACK, w=4 frames* ◆ *FLACK-M, w=4 frames*
△ *NoFLACK-ACK, w=6 frames* ▲ *FLACK-M, w=6 frames*
○ *NoFLACK-ACK, w=8 frames* ● *FLACK-M, w=8 frames*
+ *NoFLACK-ACK, w=12 frames* x *FLACK-M, w=12 frames*

Figure 7.8 Utilization versus frame error rate for various w values, C=4Mbit/s, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations



■ *SEQ-NoFLACK, w=2 frames*
◆ *SEQ-NoFLACK, w=4 frames*
▲ *SEQ-NoFLACK, w=6 frames*
● *SEQ-NoFLACK, w=8 frames*
x *SEQ-NoFLACK, w=12 frames*

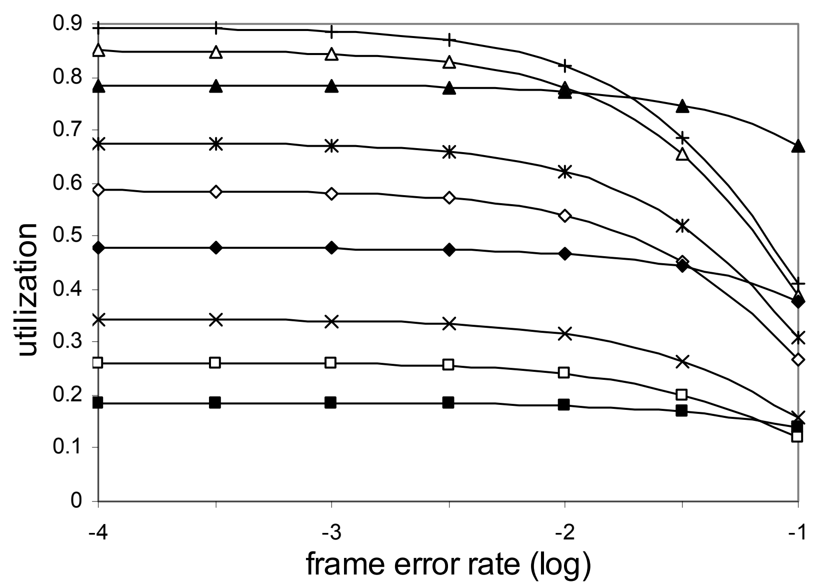
Figure 7.9 Utilization versus frame error rate for various w values, C=4Mbit/s, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations



□ *NoFLACK-ACK, l=128bytes* ■ *FLACK-M, l=128bytes* × *SEQ-NoFLACK, l=128bytes*
◇ *NoFLACK-ACK, l=512bytes* ◆ *FLACK-M, l=512bytes* ✱ *SEQ-NoFLACK, l=512bytes*
△ *NoFLACK-ACK, l=2Kbytes* ▲ *FLACK-M, l=2Kbytes* + *SEQ-NoFLACK, l=2Kbytes*

Figure 7.10 Utilization versus frame error rate for various l values, C=4Mbit/s, w=4 frames, T_t *=5sec, W=8, m=62, n=5 stations*

Fig. 7.10 shows the effect of frame size to utilization for a window size of four. Utilization is very low for small frame sizes and a high frame size implementation is needed in order to achieve high utilization. The SEQ-NoFLACK protocol always achieves a higher utilization than FLACK-M and NoFLACK-ACK. The FLACK-M protocol always outperforms the NoFLACK-ACK protocol because the implemented window size is less than the 'critical' value of six. FLACK-M is robust to FER increase but NoFLACK-ACK and SEQ-NoFLACK are also robust because a small window size is implemented. Fig. 7.11 plots the same results for a window size of sixteen. For low FER, SEQ-NoFLACK reaches the highest utilization figure and NoFLACK-ACK outperforms the FLACK-M protocol because the window size is greater than six. For high FER, FLACK-M is robust but NoFLACK-ACK and SEQ-NoFLACK protocol utilization strongly decrease because the window size is high. As a conclusion, the SEQ-NoFLACK protocol is always the best choice for small window sizes. For high window sizes, SEQ-NoFLACK is again the best choice for low FER but FLACK-M should be chosen if FER is high because it is more robust. Figures 7.10 and 7.11 show that a high frame size should be used in order to achieve high utilization. We can also conclude that AIr applications should employ a high window size and the maximum



□ *NoFLACK-ACK, l=128bytes* ■ *FLACK-M, l=128bytes* × *SEQ-NoFLACK, l=128bytes*
◇ *NoFLACK-ACK, l=512bytes* ◆ *FLACK-M, l=512bytes* ✱ *SEQ-NoFLACK, l=512bytes*
△ *NoFLACK-ACK, l=2Kbytes* ▲ *FLACK-M, l=2Kbytes* + *SEQ-NoFLACK, l=2Kbytes*

Figure 7.11 Utilization versus frame error rate for various l values, C=4Mbit/s, w=16 frames, T_t *=5sec, W=8, m=62, n=5 stations*

frame size (16Kbits) at the MAC layer in order to achieve high utilization.

7.4. RR evaluation

The performance of *L*-PPM links has been studied in the literature [1][72][79] and the successful and unsuccessful symbol capture probabilities for stations experiencing a specific SNR for different RR are derived. This section presents an analytical model that evaluates the frame error rate (f_e) as a function of SNR and RR. Based on this model, FLACK-M, NoFLACK-ACK and SEQ-NoFLACK protocol performance is studied when RR coding is employed to reach stations with low SNR. The link quality for which RR adjustment is beneficial is finally examined.

Lets assume that a symbol transmission has *L* slots, *T* is the symbol duration and that only one pulse is transmitted in one of the *L* slots with power $P\sqrt{LT}$, where *P* is constant. All the remaining *L*-1 slots are empty or 'zero'. It is assumed that the transmitted pulse is a raised cosine signal given by

$$y(t)=\left|\frac{\sin(\pi t)}{\pi t}\cdot\frac{\cos(\pi\alpha t)}{1-4\alpha^2t^2}\right| \qquad (7.26)$$

where α is a raised cosine factor in the range [0,1]. Transmissions from other stations may interfere with this transmission. The interfering signal is also assumed to be of raised cosine shape and given by

$$s(t) = \left| \frac{s_{\max} \sin(\pi t)}{\pi t} \cdot \frac{\cos(\pi \alpha t)}{1 - 4\alpha^2 t^2} \right| \tag{7.27}$$

where $s_{\max} = ISR \cdot P\sqrt{LT}$ and ISR is the interference-to-signal ratio. The interfering signal is assumed to have a random phase with respect to the transmitted signal. Thus, the amplitude of the interfering signal may have any value within the symbol period at the time of sampling at the receiver. To determine the effects of the interfering signal to the original signal reception, the interfering signal amplitude is quantized into a fixed number of discrete amplitude levels. If M levels are considered, the quantized levels are given by

$$s_i = \frac{s_{\max}(2i - 1)}{2M}, i=1,\ldots,M \tag{7.28}$$

The probability that an interfering signal of a specific level is received at the time of sampling at the receiver is given by

$$p_i = \sum_k \frac{|t_k - t_{k+1}|}{T} \tag{7.29}$$

where t_k is the instant time that the interfering signal amplitude crosses the quantization level from (i-1) to (i) and is calculated from $s(t)|_{t=t_k} = s_i - \frac{s_{\max}}{2M}$,

$$\left| \frac{\sin(\pi t_k)}{\pi t_k} \cdot \frac{\cos(\pi \alpha t_k)}{1 - 4\alpha^2 t_k^2} \right| = \frac{i-1}{M} \tag{7.30}$$

and t_{k+1} is the instant time that the interfering signal amplitude crosses the quantization level from (i) to (i+1) and is calculated from $s(t)|_{t=t_{k+1}} = s_i + \frac{s_{\max}}{2M}$,

$$\left| \frac{\sin(\pi t_{k+1})}{\pi t_{k+1}} \cdot \frac{\cos(\pi \alpha t_{k+1})}{1 - 4\alpha^2 t_{k+1}^2} \right| = \frac{i}{M} \tag{7.31}$$

With probability p_i, the received power at a slot that a pulse is originally placed is

$$y_{1i} = P\sqrt{LT}\left[1 - ISR(1 - s_i^n)\right] + \eta \quad i=1,\ldots,\mathrm{M} \tag{7.32}$$

where $s_i^n = \frac{s_i}{s_{\max}}$ is the normalized quantized level and η is white Gaussian noise with zero mean and variance σ_v^2. With probability p_i, the received power at a slot where no pulse is transmitted is given by,

$$y_{0i} = P\sqrt{LT}\,ISR(1-s_i^n)+\eta \quad i\text{=1,...,M} \tag{7.33}$$

The conditional pulse error probabilities for a 'pulse' and 'zero' (no pulse) slot in an L-PPM symbol are given by

$$p_{e1} = \sum_{i=1}^{M} p_i \mathbf{Q}\left(\frac{t_n - P\sqrt{LT}\,(1-ISR(1-s_i^n))}{\sigma_v}\right) \tag{7.34}$$

$$p_{e0} = \sum_{i=1}^{M} p_i \left(1-\mathbf{Q}\left(\frac{t_n - P\sqrt{LT}\,(ISR(1-s_i^n))}{\sigma_v}\right)\right) \tag{7.35}$$

where t_n is the normalized threshold and $\mathbf{Q}(y)$ is the Marcum error function defined as

$$\mathbf{Q}(y) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y} e^{-\frac{(x)^2}{2}}\,dx \tag{7.36}$$

Note that $t_n = 0.3P\sqrt{LT}\left(1+ISR_M\right)$ is used and that the SNR can be defined as $SNR = 10\log\left(\left(P\sqrt{LT}\right)^2/\sigma_v^2\right)$.

If the transmitter repeats a symbol RR times, the receiver implements L counters to track the number of received pulses in every symbol slot. If there is only one slot counter with the maximum value, the receiver captures the symbol in the corresponding slot. It is assumed that if two or more counters share the maximum value, the symbol is not captured, although the receiver may randomly select the correct slot. The probability that the 'pulse' slot counter has RR-i pulses is given by

$$\Phi_i^1 = \binom{RR}{i}(1-p_{e1})^{RR-i}\,p_{e1}^i \tag{7.37}$$

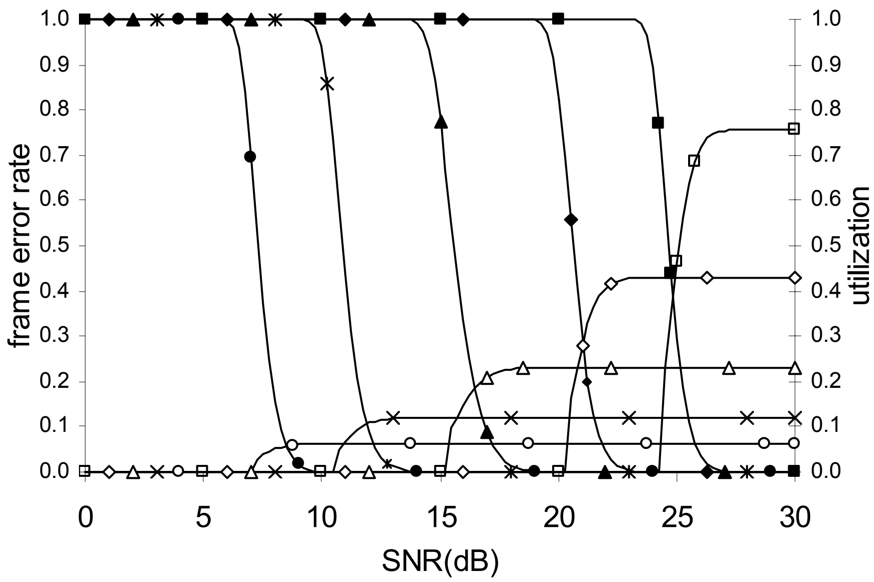
where i is the number of transmitted pulses that are not received. The probability that RR-j pulses are received in a 'zero' slot is given by

$$\Phi_j^0 = \binom{RR}{j}(1-p_{e0})^j\,p_{e0}^{RR-j} \tag{7.38}$$

The probability that all 'zero' slot counters have values less than RR-i is given by

$$\Phi^{L-1} = \left(1-\sum_{j=0}^{i}\Phi_j^0\right)^{L-1} \tag{7.39}$$

The successful symbol capture probability P_{sc} can be calculated from



□ $U_{FLACK\text{-}M}$, $RR=1$ ■ f_e, $RR=1$
◇ $U_{FLACK\text{-}M}$, $RR=2$ ◆ f_e, $RR=2$
△ $U_{FLACK\text{-}M}$, $RR=4$ ▲ f_e, $RR=4$
x $U_{FLACK\text{-}M}$, $RR=8$ ✱ f_e, $RR=8$
○ $U_{FLACK\text{-}M}$, $RR=16$ ● f_e, $RR=16$

Figure 7.12 Utilization and frame error rate versus SNR for various RR values, C=4Mbit/s, w=8 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

$$P_{sc} = \sum_{i=0}^{RR-1}\left[\Phi_i^1\left(1-\sum_{j=0}^{i}\Phi_j^0\right)^{L-1}\right] \tag{7.40}$$

Finally, the frame error rate, f_e, is given by

$$f_e = 1 - P_{sc}^{\;(l+l'_A)/\log_2 L} \tag{7.41}$$

when ADATA frames are utilized. Similarly,

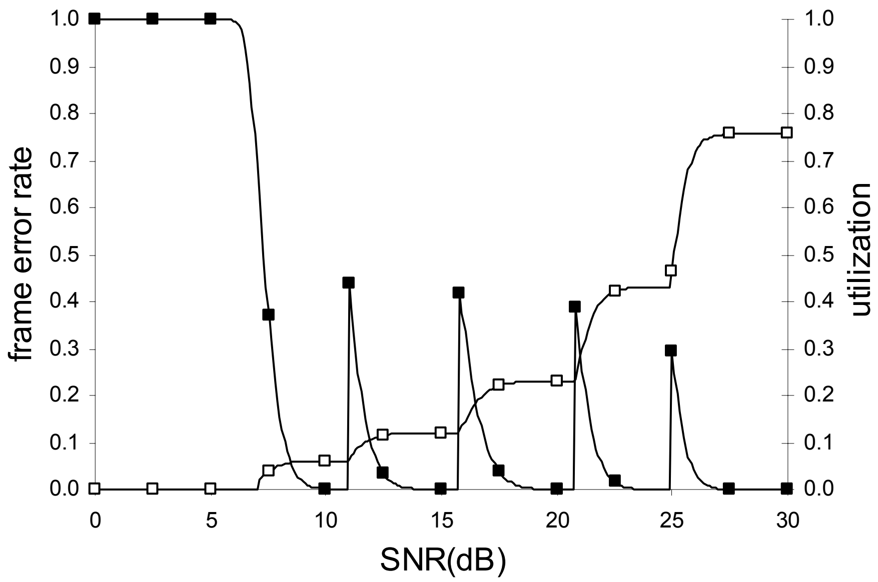
$$f_e = 1 - P_{sc}^{\;(l+l'_D)/\log_2 L} \tag{7.42}$$

when DATA frames are used and finally,

$$f_e = 1 - P_{sc}^{\;(l+l'_S)/\log_2 L} \tag{7.43}$$

when SDATA frames are utilized. Parameters *l*, l'_A, l'_D and l'_S are as defined in section 7.2; *l* is the payload data length and l'_A, l'_D and l'_S are the MBR overhead bit lengths of the ADATA, DATA and SDATA frames respectively.

Fig. 7.12 plots utilization and frame error rate (FER) versus SNR for all proposed RR values for the FLACK-M protocol for *l*=16Kbits, *ISR*=10%, t_n=0.3, α=0.75 and *M*=16. It shows that doubling RR provides approximately a 3-4dB SNR gain in FER.



□ $U_{FLACK-M}$, *optimum RR*

■ f_e, *optimum RR*

Figure 7.13 Maximum utilization and frame error rate versus SNR for optimum RR values, C=4Mbit/s, w=8 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

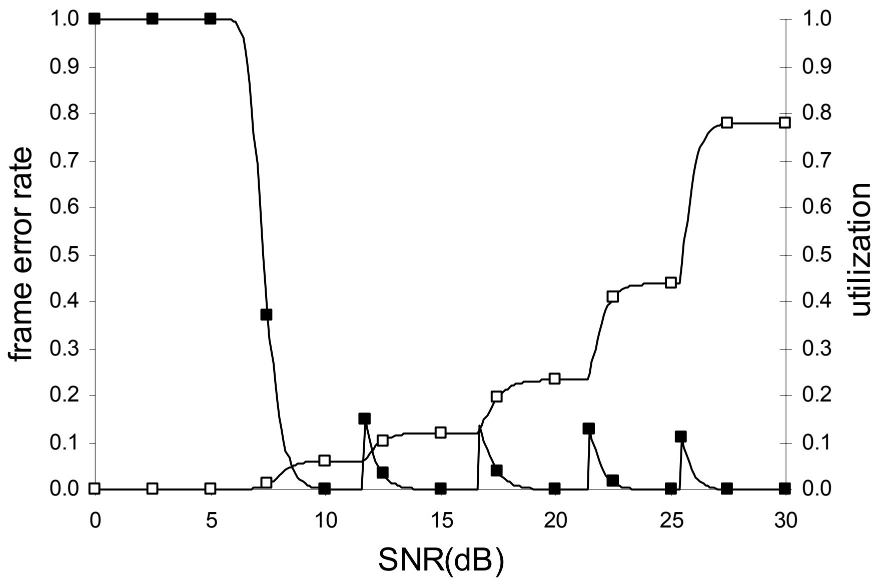
The figure shows that for a specific SNR, the smallest RR value that results in low FER should be employed. If the SNR lowers resulting in a high FER value, doubling RR results in very low FER and a LAN utilization very close to half of the original utilization.

7.5 Effectiveness of RR coding on protocol performance

When should the transmitter double the RR it implements to increase utilization? The receiver should monitor link quality and if the FER it evaluates is greater than a threshold, it should advise the transmitter to double the RR it implements. This threshold value depends on the implemented ARQ protocol.

7.5.1 FLACK-M protocol

Fig. 7.13 plots FLACK-M utilization and the corresponding FER versus SNR when RR is adjusted to the optimum value that results in maximum utilization for the specific SNR. It shows that for the considered parameter values, RR should be adjusted if FER becomes greater than approximately 0.4. This high threshold value can be explained as follows. The FLACK-M protocol implements the SW ARQ scheme at the MAC layer and employs the Reserved transfer mode with acknowledgement. Thus, a frame loss is



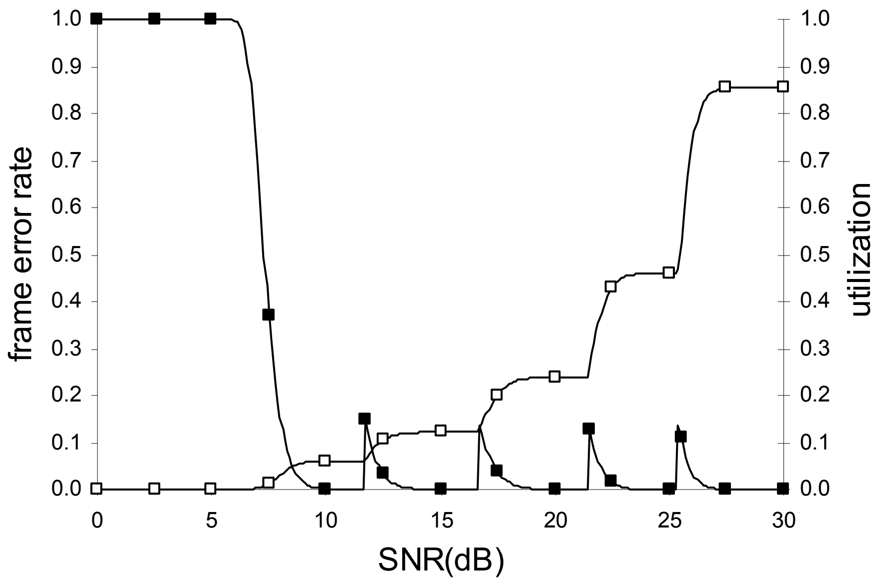
□ $U_{NoFLACK\text{-}ACK}$, *optimum RR*
■ f_e, *optimum RR*

Figure 7.14 Maximum utilization and frame error rate versus SNR for optimum RR values, C=4Mbit/s, w=8 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

immediately realized by a missing MAC ACK frame. According to the utilization definition (sections 2.7 and 6.1), if RR is doubled to cope with transmission errors, utilization is halved. Thus, if significantly more than half of the transmitted frames are received correctly, RR should not be doubled. Results produced for different window and frame sizes indicate that the FER threshold is practically independent of the window size and that it lowers for lower frame sizes.

7.5.2 NoFLACK-ACK protocol

Fig. 7.14 plots NoFLACK-ACK utilization and the corresponding FER versus SNR when RR is adjusted to the optimum value for the specific SNR. The FER threshold lowers to approximately 0.15. The reason is that the NoFLACK-ACK protocol implements a GBN ARQ scheme and correctly received frames following an error frame in a window transmission are considered as out of sequence and are discarded by the receiver. As a result, a frame error causes the retransmission of the error frame and of the frames following it in the same window. Thus, NoFLACK ACK protocol is more sensitive to FER increase than FLACK-M protocol and a lower FER threshold is needed. Produced results also indicate that the FER threshold lowers with window size increase and increases for smaller window sizes. The FER threshold also depends on



□ $U_{SEQ\text{-}NoFLACK}$, *optimum RR*
■ f_e, *optimum RR*

Figure 7.15 Maximum utilization and frame error rate versus SNR for optimum RR values, C=4Mbit/s, w=8 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

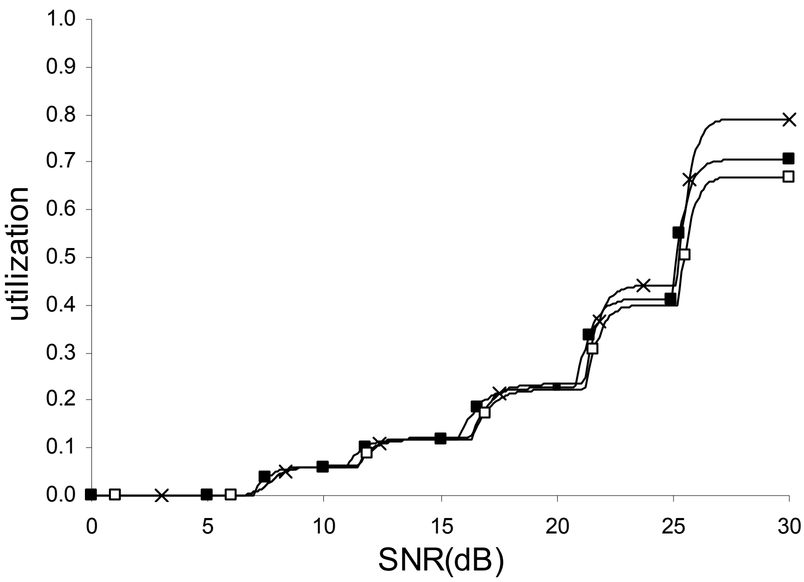
frame size and lowers when a smaller than the maximum (=16Kbits) frame size is employed. However, as discussed in section 7.3, a low frame size implementation results in low utilization.

7.5.3 SEQ-NoFLACK protocol

Similarly, Fig. 7.15 plots SEQ-NoFLACK utilization and the corresponding FER versus SNR for optimum RR adjustment. Direct comparison with Fig. 7.14 shows that the FER threshold of the SEQ-NoFLACK is identical to that of the NoFLACK-ACK protocol. This result can be explained by considering that both protocols implement a GBN ARQ scheme and retransmit the same frames in the case of a frame loss. However, as SEQ-NoFLACK incurs smaller delays, a higher utilization is achieved.

7.5.4 Performance evaluation

Fig. 7.16 compares utilization versus SNR for optimum RR values for the FLACK-M, NoFLACK-ACK and SEQ-NoFLACK protocols. It shows that FLACK-M always achieves a higher utilization than NoFLACK-ACK protocol because, as discussed in section 7.3.3, the implemented window size of four frames is less than the ‘critical’ value of six frames. SEQ-NoFLACK always achieves the highest utilization among the

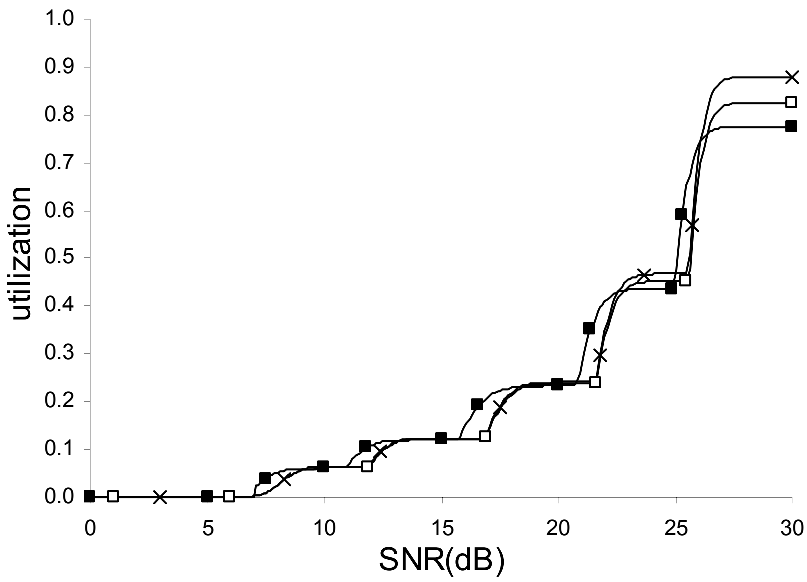


□ *NoFLACK-ACK, optimum RR*
■ *FLACK-M, optimum RR*
x *SEQ-NoFLACK, optimum RR*

Figure 7.16 Utilization versus SNR for optimum RR values, C=4Mbit/s, w=4 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

considered protocols. These results can be explained by considering that for small window sizes (four for example) all protocols are robust to FER increase, a conclusion drawn in the previous section. The protocol that incurs the least overhead always achieves the highest utilization. Fig. 7.17 plots the same utilization results for a window size of twelve. In this case, a different behavior is observed. SEQ-NoFLACK always outperforms NoFLACK-ACK; NoFLACK-ACK outperforms FLACK-M for most SNR values because the implemented window size of twelve is greater that the 'critical' value of six. However, as discussed in section 7.3.3 for large window size values, the SEQ-NoFLACK and NoFLACK-ACK protocols are not robust to FER increase; FLACK-M remains robust. As a result, for certain SNR values FLACK-M highly outperforms SEQ-NoFLACK and NoFLACK-ACK protocols. For example, if the SNR is 25.5 dB, FLACK-M reaches a 0.65 utilization figure and highly outperforms the SEQ-NoFLACK utilization of 0.47. The reason is that when the SNR results in low FER values, utilization slightly drops for the robust FLACK-M protocol; utilization highly drops for the non-robust SEQ-NoFLACK and NoFLACK-ACK protocols forcing a higher RR value employment and a utilization drop.

We can conclude that for low window sizes, SEQ-NoFLACK is always the best



□ *NoFLACK-ACK, optimum RR*
■ *FLACK-M, optimum RR*
x *SEQ-NoFLACK, optimum RR*

Figure 7.17 Utilization versus SNR for optimum RR values, C=4Mbit/s, w=12 frames, l=2Kbytes, T_t =5sec, W=8, m=62, n=5 stations, ISR=10%, t_n=0.3, α=0.75, M=16

choice and FLACK-M outperforms the NoFLACK-ACK protocol. For high window sizes, SEQ-NoFLACK always outperforms the NoFLACK-ACK protocol. FLACK-M offers the best choice for a few SNR value intervals but, at the same time, the worst choice for the remaining SNR values. Thus, maximum utilization is achieved if the suitable ARQ protocol is selected for the enforced window size and for the receiver's SNR.