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Packet level acknowledgement and Go-Back-N protocol performance in infrared wireless LANs

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SUMMARY

Infrared wireless LANs may employ repetition rate (RR) coding to increase the symbol capture probability at the receiver. This paper examines the effectiveness of RR coding to utilization for infrared LANs using the physical and link layer parameter values proposed in the Advanced Infrared (AIr) protocol standard, which is developed by the Infrared Data Association (IrDA). Infrared LANs employ a Go-Back-N (GBN) automatic repeat request (ARQ) retransmission scheme at the Link Control (LC) layer to ensure reliable information transfer. To efficiently implement RR coding, the receiver may return after every DATA packet a suggestion for the suitable RR value to be used by the transmitter and implement a Stop-and-Wait (SW) ARQ scheme at the medium access control (MAC) layer. The effectiveness of employing this optional SW ARQ scheme at the MAC layer is discussed. Analytical models for the ARQ retransmission schemes are developed and employed to compare protocol utilization for different link parameter values such as window size, packet length and LC time out periods. This analysis identifies the ARQ protocol that maximizes performance for the specific link quality and the implemented link layer parameters. The effectiveness of the proposed RR coding to LAN utilization for different ARQ scheme implementation is finally explored. This analysis identifies the link quality level at which RR should be adjusted for maximum performance. It is concluded that if the packet error rate is higher than 0.1–0.4 (depending on the implemented ARQ protocol), the receiver should advise the transmitter to double the implemented RR for maximum performance. These error rate values are high and can be effectively estimated by the transmitter based on packet retransmissions. Thus, the usefulness of the receiver indicating to the transmitter to adjust RR is questionable, as the transmitter can effectively implement the suitable RR value based on packet retransmissions. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: infrared wireless LANs; IrDA; ARQ protocols; repetition rate coding

1. INTRODUCTION

The need for wireless connectivity is increasing with the growth of the number of portable computers and hand held devices. The need to connect a number of such devices in a wireless LAN is also increasing. The use of wireless Infrared (IR) links has been considered as a possible

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candidate for wireless LANs [1–4]. Infrared systems are confined to the room of operation, have very high bandwidth, high data rates, small physical size, low cost, low power and utilize an unregulated spectrum [1, 5]. However, IR link signal-to-noise ratio (SNR) is affected by sunlight, fluorescent light, diffuse propagation paths and physical obstacles obstructing the line of sight [5]. IR links should be of high dynamic range and capable of operating under variable SNR. As IR wireless links may suffer from transmission errors, a reliable retransmission scheme is required to ensure correct reception of the transmitted information.

Infrared Data Association (IrDA) was formed in 1993 aiming to develop standards for indoor connectivity using the infrared spectrum. IrDA developed the IrDA 1.x protocol standard [1, 6] for low cost, short range, narrow beam, point-to-point and half-duplex links [7]. The success of IrDA 1.x standard can be measured by the number of mobile devices on market today, ranging from laptops to mobile phones, embedding a low-cost infrared port for wireless communications. IrDA has proposed the Advanced Infrared (AIr) protocol standard for wireless LANs [2, 8]. IrLAP, the IrDA 1.x data link layer [9], was split into three sub-layers, the AIr medium access control (AIr-MAC) [10], the AIr link manager (AIr-LM) and the AIr link control (AIr-LC) [11] sub-layers. A new physical layer, AIr PHY [8, 12], is proposed employing wide angle infrared ports capable of operating at angles up to $\pm 60°$. AIr PHY employs a four-slot pulse position modulation with variable repetition encoding (4PPM/VR) format. The base data rate is 4 Mbps. The transmitter utilizes repetition rate (RR) coding for operation at a low SNR [4, 13]. Every transmitted symbol is repeated RR times in order to increase the symbol capture probability at the receiver. RR coding results in a improved link quality at the expense of lower link data rate. The receiver monitors channel quality and advises the transmitter of the suitable RR to be used [10]. RR coding is a way of adapting the link rate to channel conditions. AIr protocol also uses the request-to-send/clear-to-send (RTS/CTS) packet exchange to reserve the infrared medium and to cope with hidden stations [14]. A successful reservation is always terminated by using the end-of-burst/end-of-burst confirm (EOB/EOBC) packet exchange to inform all stations that the current reservation is over and to synchronize all competing stations in contending for medium access.

This work considers AIr MAC and LC layer implementation by identifying the link layer issues and parameters that maximize performance, such as the reliable retransmission scheme, suitable RR value, the transmission control passing mechanism and window and frame size. AIr protocol proposes a Go-Back-N (GBN) automatic repeat request (ARQ) retransmission scheme at the LC layer [11, 15]. To efficiently implement RR coding under varying SNR, the receiver may return after every DATA packet a suggestion for the suitable RR value to be used for the specific SNR. As the packet carrying this suggestion also acknowledges the received DATA packet, an optional Stop-and-Wait (SW) ARQ scheme at the medium access control (MAC) layer is implemented [10, 15]. The effectiveness of using the optional SW ARQ scheme at the MAC layer when the GBN ARQ scheme is implemented at the LC layer is studied in References [15, 16] for LANs with one transmitting station. Presented results are enhanced for the same ARQ schemes (referred to as PLACK and NoPLACK protocols) in References [17, 18]. This work offers a complete analysis of AIr's ARQ schemes by considering (in addition to PLACK and NoPLACK protocols) variations of the proposed ARQ schemes (referred to as PLACK-M and NoPLACK-ACK protocols) that result in better performance. This work also considers LANs with many transmitting stations.

The GBN ARQ scheme passes transmission control by setting the Poll/Final (P/F) bit in the control field of a transmitted packet. AIr LC specification [11] defines that the P/F bit may be set in a DATA or in an LC Receive Ready acknowledgement (ACK) packet. This paper compares the effectiveness to utilization of setting the P/F bit in a DATA or in an ACK packet at the LC layer. AIr LC may also rely on MAC's SW ARQ scheme to guarantee that the transmitted information is correctly received. In this case, the transmitter does not implement the GBN ARQ scheme at the LC layer, it does not solicit a response by setting the P/F bit of a transmitted packet and no LC ACK packets are transmitted. The receiver acknowledges correctly received packets by using the MAC ACK packets of the SW ARQ scheme. This paper also explores the effectiveness of utilizing the optional SW ARQ scheme of the MAC layer. Analytical models for links employing MAC's SW ARQ scheme and/or LC's GBN ARQ scheme are presented. Special cases of setting the P/F bit in DATA or LC ACK packets are also considered. A comparison of the utilization of retransmission schemes when variable repetition rate coding is implemented is included. The SNR is identified at which the RR should be adjusted for maximum performance for the specific ARQ protocol and for the utilized link layer parameters, such as window size, packet size and timer values.

2. PROTOCOL DESCRIPTION

Packet level acknowledgement (PLACK) protocol utilizes the GBN ARQ scheme at the LC layer and the SW ARQ scheme at the MAC layer (Figure 1). PLACK is a two-layer ARQ scheme where a GBN ARQ scheme is implemented on top of an SW ARQ scheme [16]. However, AIr LC specification [11] also defines that the LC layer may rely on the MAC layer's reliable information delivery schemes to guarantee that the transmitted DATA packets 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. Packet level acknowledgement MAC (PLACK-M) protocol employs the SW ARQ scheme at the MAC layer and no ARQ scheme at the LC layer (Figure 2).

Figures 1 and 2 portray PLACK and PLACK-M operation, respectively, for a window size of 4. The transmitter sends a DATA packet and waits for the corresponding MAC ACK packet. If the DATA packet is correctly received, the receiver awaits a turn around time (TAT) to allow the transmitter's circuitry to recover and transmits an MAC ACK packet. If the MAC ACK

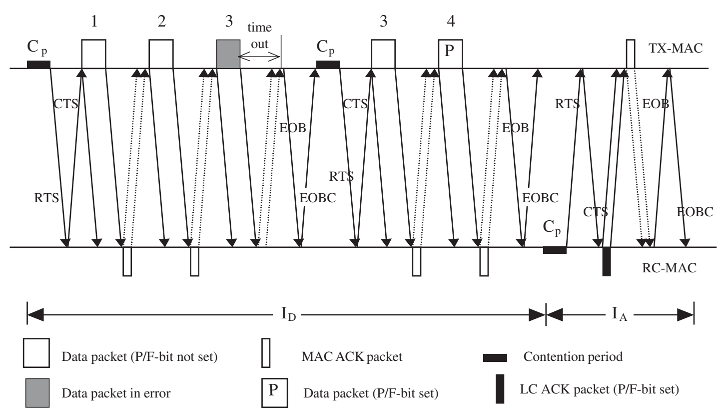

Figure 1. PLACK protocol (SW ARQ at the MAC layer and GBN at the LC layer).

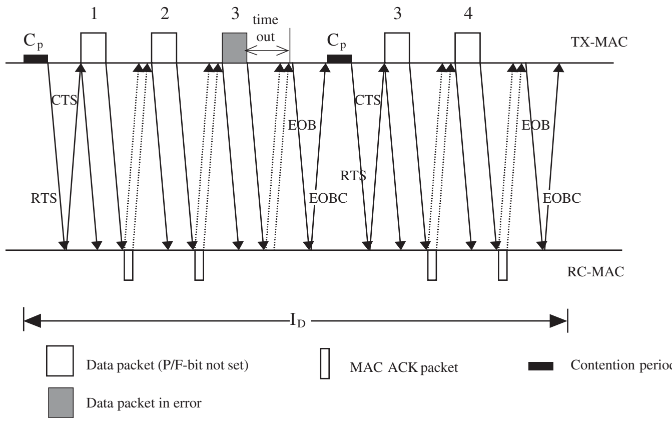

Figure 2. PLACK-M protocol (SW ARQ at the MAC layer and no ARQ scheme at the LC layer).

packet is received, indicating correct reception of the DATA packet, the transmitter proceeds with the transmission of the next packet. Figures 1 and 2 assume that packet 3 is lost. When the timer for the responding MAC ACK packet expires, the transmitter terminates current reservation and contends again for medium access in an effort to transmit the remaining packets during the next successful reservation. The considered MAC ACK time out period equals the time required for receiving the MAC ACK packet. PLACK and PLACK-M protocols cannot take advantage of the sliding window mechanism. As a result, the next reservation contains only packets 3 and 4 not a full window transmission. If PLACK-M protocol is implemented (Figure 2), the transmitter does not set the P/F bit in the last DATA packet in a window transmission because PLACK-M does not employ a GBN ARQ scheme at the LC layer. If PLACK protocol is implemented (Figure 1), the transmitter sets the P/F bit in the last DATA packet it transmits and the receiver responds with an LC ACK packet as shown in Figure 1. If this DATA packet is lost, the P/F bit loss is immediately realized by a MAC ACK time out expiration for the corresponding acknowledgement and the transmitter contends again in order to retransmit the last DATA packet.

An alternative is for the LC layer to employ a GBN ARQ scheme and to disable the optional MAC layer SW ARQ scheme [11]. LC GBN scheme sets the P/F bit in the control field of a transmitted packet to pass transmission control. Two different operation modes are considered for the LC GBN ARQ scheme. The first always sets the P/F bit in the last DATA packet in a window transmission (Figure 3); the second always sets the P/F bit in a special LC ACK packet that follows the last DATA packet in a window transmission (Figure 4). No packet level acknowledgement (NoPLACK) protocol utilizes the GBN ARQ scheme at the LC layer, no ARQ scheme at the MAC layer and utilizes DATA packets to carry the P/F bit to the receiver (Figure 3). No packet level acknowledgement protocol utilizing LC ACK packets (NoPLACK-ACK) uses the GBN ARQ scheme at the LC layer, no ARQ scheme at the MAC layer and always utilizes LC ACK packets to carry the P/F bit to the receiver (Figure 4).

In NoPLACK protocol, the transmitter solicits a response by setting the P/F bit in the last DATA packet it transmits. The receiver acknowledges correctly received packets and returns transmission control by setting the P/F bit in the responding LC ACK packet. When DATA packets are large and link error rate is high, the DATA packet carrying the P/F bit may be lost.

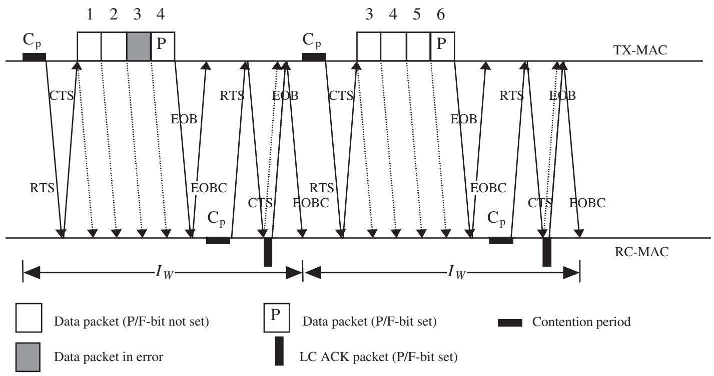

Figure 3. NoPLACK protocol (no ARQ at the MAC layer, GBN at the LC layer and P/F bit in DATA packet).

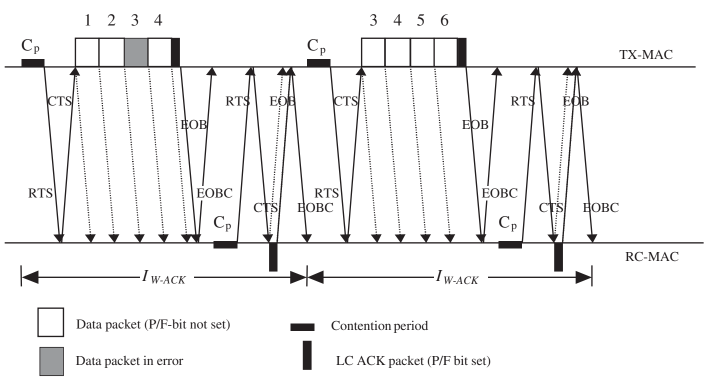

Figure 4. NoPLACK-ACK protocol (no ARQ at the MAC layer, GBN at the LC layer and P/F bit in ACK packet).

In this case the receiver fails to acknowledge correctly received packets because it assumes that the transmitter wishes to send more DATA packets 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 packet with the P/F bit set. The receiver responds with an LC ACK packet with the P/F bit set, acknowledging correctly received packets and returning transmission control. NoPLACK-ACK protocol reduces the P/F bit loss probability by not setting the P/F bit in the last DATA packet in a window transmission and by transmitting a new (and much smaller) LC ACK packet carrying the P/F bit following the last DATA packet in a window transmission. NoPLACK-ACK protocol reduces the P/F bit loss probability at the expense of transmitting a new LC ACK packet.

Figures 3 and 4 show NoPLACK and NoPLACK-ACK protocol operation, respectively. The transmitter transmits a window of packets upon gaining access to the infrared medium. In NoPLACK protocol (Figure 3) the transmitter sets the P/F bit in packet 4; in NoPLACK-ACK (Figure 4) it does not and transmits a new LC ACK packet with the P/F bit set following packet 4. Upon receiving a packet with the P/F bit set, the receiver contends for the medium and responds with an LC ACK packet informing the transmitter of the correctly received packets.

The LC ACK packet has the P/F bit set returning transmission control to the transmitter. If all packets are correctly received, the transmitter sends the next window of packets. Otherwise, it repeats the erred packet and retransmits all packets that followed the erred packet during the previous window transmission. By taking advantage of the sliding window mechanism, the transmitter also sends new packets to form a complete window transmission. If again packet 3 is lost (Figures 3 and 4), both protocols retransmit packets 3 and 4 and transmit new packets 5 and 6 to form a complete window transmission. If the packet carrying the P/F bit is lost, the information transfer procedure is stopped. The situation is resolved by a transmitter's LC time out expiration. Current analysis assumes that LC ACK packets are very small and are always correctly received. This is a valid assumption because the highest LC ACK error rate for the considered scenarios is 0.0003, which can be safely neglected.

3. PROTOCOL ANALYSIS

We consider an LAN of n transmitting stations operating in saturation conditions, i.e. all n stations always have a window of packets ready for transmission. We present analytical models that evaluate the channel utilization, which is defined as the time portion that the infrared medium is used to transmit successful payload data. The analysis assumes that the one way propagation delay is very small and can be safely neglected. The analysis considers the preparation time of a DATA packet and assumes that the processing time of a received DATA or ACK packet is smaller than the TAT and can overlap with the TAT delay (no additional received packet processing time is calculated). The receiver processes the received packet and then waits until a total of TAT delay is reached before transmitting the suitable response. The proposed value of 200 μs for the TAT delay is used. It is also assumed that the processing time of a received packet can also overlap with the reception of the next packet and it is not additive.

3.1. PLACK utilization

The utilization of the PLACK protocol can be calculated by considering the number of reservations required to successfully transmit a window of w packets. For packet error rate p_e, the probability $P_{s/i}$ of successful transmission of all packets when i reservations are required is given by [16]

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

where

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

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

$$T_D(i) = i(C_p + D) + (w + i - 1)(t + F + p_1 + E) \tag{3}$$

where C_p is the average contention period (including empty and collision slots) for a successful reservation, D is the reservation overhead that includes the transmission time of the RTS, CTS, EOB and EOBC packets and the TAT delays that follow these packets, t is the data payload transmission time, F is the transmission time of DATA packet overheads (preamble, robust header, CRC, etc.), p_1 is the preparation time of a data packet and E is the transmission time required for an MAC layer acknowledgement packet. E also includes the TAT delays associated with this transmission. The value of t is given by

$$t = \frac{\mathrm{RR}l}{C} \tag{4}$$

where RR is the repetition rate, l is the packet length and C is the data rate. The transmission time, I_D, for a complete w packet transmission is derived as

$$I_D = \sum_{i=1}^{\infty} P_{s/i} T_D(i) \tag{5}$$

Assuming that the LC ACK packets are very small and are always transmitted error free, the transmission time of the LC ACK packet is given by

$$I_A = (C_p + D) + (t_{\mathrm{ack}} + p_1 + E) \tag{6}$$

where t_{ack} is the LC layer ACK packet transmission time and the other parameters are the same. E in Equation (6) stands for the time needed to acknowledge the LC ACK packet at the MAC layer. The PLACK protocol utilization can now be derived as

$$U_{\mathrm{PLACK}} = \frac{wt}{\mathrm{RR}(I_D + I_A)} \tag{7}$$

3.2. *PLACK-M utilization*

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

$$U_{\mathrm{PLACK\text{-}M}} = \frac{wt}{\mathrm{RR}I_D} \tag{8}$$

where I_D is given by Equation (5).

3.3. *NoPLACK-ACK protocol*

The utilization of NoPLACK-ACK protocol is defined by the help of References [16, 19, 20]

$$U_{\mathrm{NoPLACK\text{-}ACK}} = \frac{t}{\mathrm{RR}} \frac{1 - p_e}{p_e} \frac{(1 - (1 - p_e)^w)}{I_{\mathrm{W\text{-}ACK}}} \tag{9}$$

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

$$I_{\mathrm{W\text{-}ACK}} = 2(C_p + D) + w(t + F + p_1) + 2(p_1 + t_{\mathrm{ack}}) \tag{10}$$

using the same parameter definitions for C_p, D, etc. as in the PLACK protocol.

3.4. *NoPLACK utilization*

If NoPLACK protocol is implemented and the DATA packet carrying the P/F bit is lost, the information transfer procedure is halted and restarted again when the LC timer expires. During the time out period and if the IR LAN consists of only one pair of stations, the link idle time results in LAN utilization degradation. However, if many stations are transmitting in the LAN, the LAN 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. In evaluating LAN utilization, we use the NoPLACK_1 notation to refer to the lower limit of NoPLACK utilization. NoPLACK_1 corresponds to NoPLACK protocol scenario when only one station is transmitting in the LAN and the infrared medium is idle for the entire LC time out period when a P/F bit is lost. We also use the NoPLACK_N notation to refer to the upper limit of NoPLACK utilization. NoPLACK_N corresponds to NoPLACK protocol scenario when a significant (or infinite) number of stations are transmitting in the infrared LAN and the infrared medium is equally utilized by the remaining stations in the case of one or more simultaneous P/F bit losses. In this case, the LAN utilization is not decreased but the utilization of every transmitting individual station is temporarily increased when one or more stations temporarily stop transmitting. Thus, it is expected that all real life network scenarios implementing NoPLACK protocol will achieve an LAN utilization with an upper limit of the NoPLACK_N utilization and a lower limit of the NoPLACK_1 utilization.

NoPLACK_1 utilization can be evaluated by the help of References [16, 19, 20]

$$U_{\text{NoPLACK}_1} = \frac{t}{\text{RR}} \frac{1 - p_e}{p_e} \frac{(1 - (1 - p_e)^w)}{I_{w-1}} \tag{11}$$

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

$$\begin{aligned} I_{w-1} = {} & 2(C_1 + D) + w(t + F + p_1) + p_1 + t_{\text{ack}} \\ & + p_{\text{e}}(T_t + C_1 + D + p_1 + t_{\text{ack}}) \end{aligned} \tag{12}$$

where T_t is the LC layer time out period, C_1 is the average contention period for a successful reservation when only one station is transmitting and the other parameters are the same. When only one station contends for medium access, there are no collisions. Thus, the contention period consists of empty slots only and C_1 is given by

$$C_1 = \frac{\text{CW}_{\min} - 1}{2} t_{\text{slot}} \tag{13}$$

where $\text{CW}_{\min}$ is the minimum contention window size and t_{slot} is the collision avoidance slot duration. According to AIr specifications [10, 11], $\text{CW}_{\min} = 8$ and $t_{\text{slot}} = 800\ \mu\text{s}$.

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

$$U_{\text{NoPLACK-N}} = \frac{t}{\text{RR}} \frac{1 - p_e}{p_e} \frac{(1 - (1 - p_e)^w)}{I_{W-N}} \tag{14}$$

and I_{W-N} is given by

$$I_{W-N} = 2(C_p + D) + w(t + F + p_1) + p_1 + t_{\text{ack}} + p_{\text{e}}(C_p + D + p_1 + t_{\text{ack}}) \tag{15}$$

4. PROTOCOL PERFORMANCE EVALUATION

Based on the analysis presented in the previous section, protocol utilization is compared under the assumption that no repetition rate (RR = 1) coding is implemented. First, NoPLACK and NoPLACK-ACK protocols are compared and results indicate that NoPLACK-ACK is usually a better choice. Then, PLACK and PLACK-M protocols are compared and results indicate that PLACK-M offers a significantly higher utilization for the same link layer parameter values.

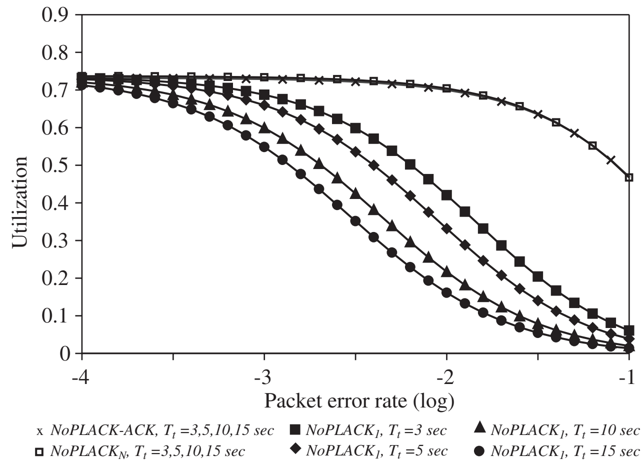

Figure 5. Utilization versus packet error rate for various T_t values, $C_p = 2.8$ ms, $w = 8$ packets, $C = 4$M bit/s, $l = 2$ Kbytes, $RR = 1$.

Finally, NoPLACK-ACK and PLACK-M protocols are compared for different link layer parameter values. According to AIr MAC specification [10], the implemented values for D, E and F are 1.74 ms, 632 and 250 μs, respectively.

Figure 5 plots utilization versus packet error rate (PER) for NoPLACK-ACK protocol and for NoPLACK_1 and NoPLACK_N protocol scenarios for different LC time out values. It shows that NoPLACK-ACK protocol achieves slightly lower (virtually identical) performance than the NoPLACK_N protocol scenario. The reason is that the additional LC ACK packet utilized by the NoPLACK-ACK protocol causes a small additional delay compared with other protocol delays such as contention periods, RTS/CTS exchanges, etc. Figure 5 also shows that utilization degrades with PER increase but NoPLACK_1 protocol is more sensitive. The NoPLACK_1 utilization drop worsens with T_t value increase. The reason for this is that NoPLACK relies on the successful transmission of the last DATA packet to carry the P/F bit to the receiver. If the last DATA packet is lost, the situation is resolved by an LC layer time out. As NoPLACK_1 utilization assumes that the infrared medium is idle for the entire T_t time out period, utilization degradation is increased for higher T_t values. Figure 6 plots utilization versus PER for different window size values for $l = 2$ Kbytes. It shows that, for low PER, utilization is high only for high w values. NoPLACK_N utilization is slightly higher (virtually identical) than NoPLACK-ACK utilization for the considered PER values. Utilization results produced for smaller l values validate the expressed conclusion that NoPLACK_N utilization is always virtually identical to NoPLACK-ACK utilization. If NoPLACK protocol is implemented, the LAN utilization ranges from NoPLACK_1 utilization (if only one station transmits in the LAN) to NoPLACK_N utilization (if many stations are transmitting fully utilizing T_t periods). As NoPLACK-ACK utilization is slightly lower than NoPLACK_N utilization and independent of the number of the transmitting stations in the LAN, NoPLACK-ACK protocol is a much better choice. Therefore, NoPLACK-ACK protocol is considered for the rest of this evaluation. As a conclusion, the P/F bit should be set only in LC ACK packets if the MAC's SW ARQ scheme is not employed.

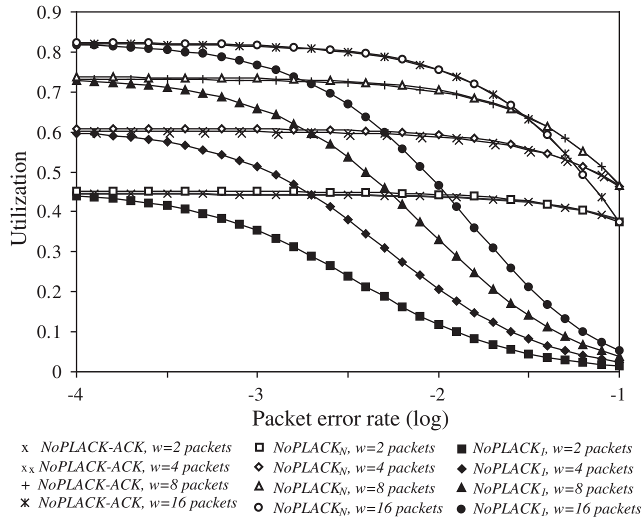

Figure 6. Utilization versus packet error rate for various w values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $RR = 1$.

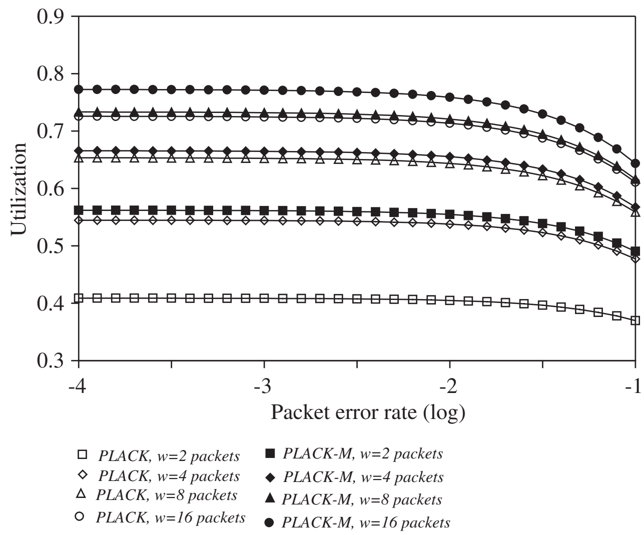

Figure 7. Utilization versus packet error rate for various w values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $RR = 1$.

Figure 7 compares PLACK and PLACK-M utilization versus PER for different window size values. It shows that PLACK-M utilization is significantly higher than PLACK utilization for the same window size value. This result is explained by considering that PLACK is a two-way ARQ system. PLACK implements an additional GBN ARQ scheme at the LC layer resulting in the transmission of additional LC ACK packets, additional RTS/CTS packet exchanges, contention periods, etc. Figure 7 also shows that the PLACK protocol needs to more than

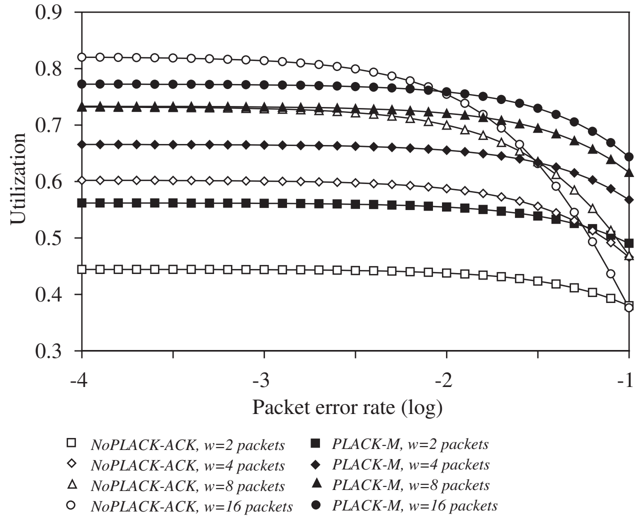

Figure 8. Utilization versus packet error rate for various w values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $RR = 1$.

double the implemented window size to reach a utilization figure close to PLACK-M protocol utilization. Utilization results produced for smaller l values indicate that this conclusion is always true and independent of the implemented packet size. Considering that AIr protocol achieves high utilization only for high window size values and as the window size parameter is application dependent and thus not directly controllable at the MAC layer, PLACK-M protocol is a much better choice. Therefore, PLACK-M protocol is considered for the rest of this evaluation. As a conclusion, when the LC layer utilizes the MAC SW ARQ scheme, it should not implement its GBN ARQ scheme and should rely on MAC's reliable data delivery techniques to guarantee that the transmitted information was actually received by the remote station.

Figure 8 compares PLACK-M and NoPLACK-ACK utilization for different window size values for $C_p = 2.8$ ms. It reveals that, for low PER and for small window size values, the PLACK-M protocol performs better than the NoPLACK-ACK protocol but the situation is reversed for high window size values. It is concluded that for $C_p = 2.8$ ms, the PLACK-M protocol should be implemented for burst transmissions of less than eight packets and that the NoPLACK-ACK protocol is preferable for burst transmissions consisting of more than eight packets. Figure 8 also shows that PLACK-M is more robust than NoPLACK-ACK to PER increase. Figure 9 plots the same results for a small C_p of 0.4 ms. It shows that, for low PER, the 'critical' value of eight packets has been lowered to four packets and NoPLACK-ACK protocol achieves a higher utilization if a window size value greater than four is used. As a conclusion, PLACK-M protocol should be implemented if the window size used is smaller than a 'critical' value; NoPLACK-ACK protocol otherwise. The 'critical' window size value increases with C_p increase, which depends on the number of the transmitting stations in the network.

Figure 10 shows the effect of C_p to protocol performance by plotting PLACK-M and NoPLACK-ACK utilization versus C_p for different PER values. Figure shows that NoPLACK-ACK is more sensitive than PLACK-M to C_p increase because NoPLACK-ACK contends

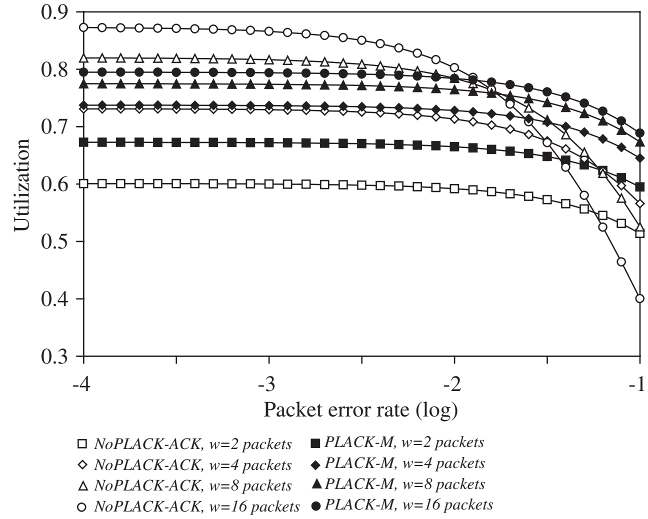

Figure 9. Utilization versus packet error rate for various w values, $C_p = 0.4\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $RR = 1$.

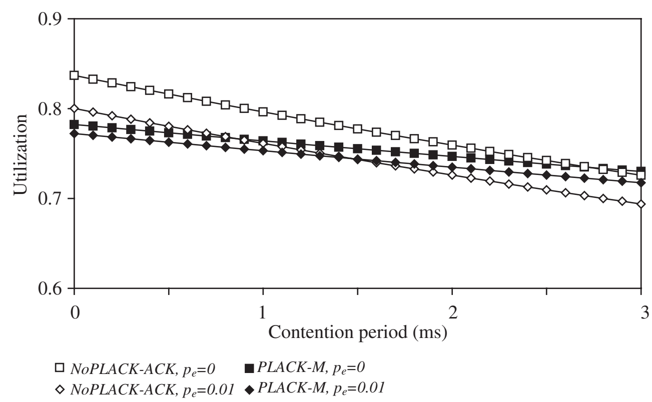

Figure 10. Utilization versus Contention period for various p_e values, $w = 8$ packets, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $RR = 1$.

twice where as PLACK-M contends only once for a complete window transmission. It also shows that NoPLACK-ACK is better for low C_p but the situation is reversed for high C_p values. Figure 11 shows the effect of packet size to utilization for a window size of 4. PLACK-M protocol always outperforms NoPLACK-ACK protocol because the implemented window size is less than the 'critical' value of 8 for $C_p = 2.8$ ms. The utilization is very low for small packet sizes and NoPLACK-ACK is robust to PER increase because a small window size is implemented. Figure 12 plots the same utilization results for a window size of 16. NoPLACK-ACK outperforms PLACK-M for low PER because the window size is greater than 8 but NoPLACK-ACK utilization strongly depends on PER for such high window size values. Only for high window sizes and low error rates the NoPLACK-ACK protocol performs better than

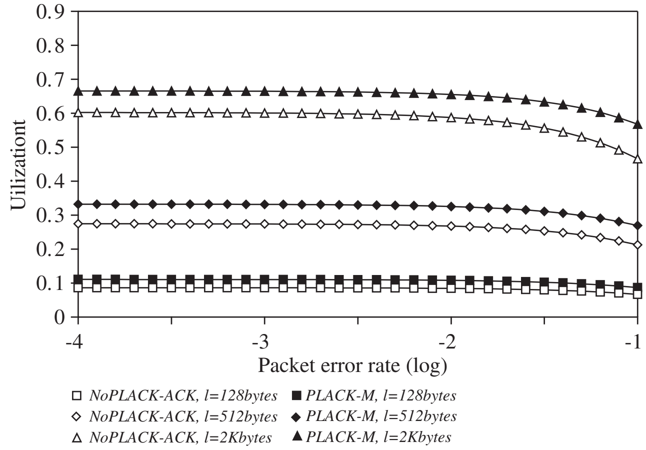

Figure 11. Utilization versus packet error rate for various l values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $w = 4$ packets, $RR = 1$.

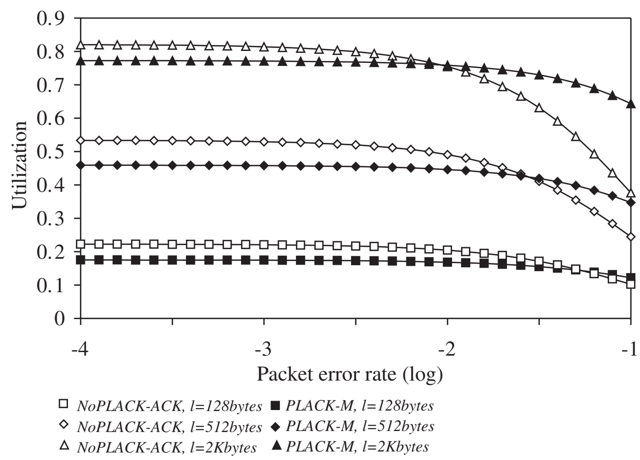

Figure 12. Utilization versus packet error rate for various l values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $w = 16$ packets, $RR = 1$.

the PLACK-M protocol. Figures 11 and 12 show that a high packet size should be used in order to achieve high utilization. As a conclusion, AIr achieves high utilization when high window and packet sizes are implemented.

5. RR EVALUATION

Protocol performance is affected by packet error rate. Packet error rate depends on SNR, a physical layer parameter. AIr utilizes 4-PPM encoding and RR coding is used to communicate with stations with low SNR. The performance of L-PPM links has been studied in References

[21–23] and the successful and unsuccessful symbol capture probabilities for stations experiencing a given SNR as a function of RR are derived. This section presents an analysis that evaluates the packet error rate as a function of SNR and RR. The effectiveness of RR coding to packet error rate and to utilization is examined and the point at which RR should be adjusted for maximum utilization is identified. Finally, NoPLACK-ACK utilization is compared to PLACK-M protocol utilization for links implementing the proposed RR coding.

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

$$y(t) = \left| \frac{\sin(\pi t)}{\pi t} \frac{\cos(\pi \alpha t)}{1 - 4\alpha^2 t^2} \right|, \quad t \in \left(-\frac{T}{2}, \frac{T}{2} \right) \tag{16}$$

where α is a raised cosine factor in the range [0,1]. Interfering signal caused by other stations transmissions is considered. The interfering signal is also assumed to be of raised cosine shape and given by

$$s(t) = \left| \frac{s_{\max} \sin(\pi t)}{\pi t} \frac{\cos(\pi \alpha t)}{1 - 4\alpha^2 t^2} \right|, \quad t \in \left(-\frac{T}{2}, \frac{T}{2} \right) \tag{17}$$

where $s_{\max} = \mathrm{ISR}\ P\sqrt{\mathrm{LT}}$ and ISR is the interference to signal ratio. The interfering signal is assumed to have a random delay with respect to the transmitted signal. Interfering signal amplitude may have any value within the symbol period at the time of sampling at the receiver. The interfering signal amplitude is quantized into a fixed number of discrete amplitude levels in order to calculate its effects to the original signal reception [21]. If M levels are considered, the quantized levels are given by

$$s_i = \frac{s_{\max}(2i - 1)}{2M}, \quad i = 1, \ldots, M \tag{18}$$

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

$$p_i = \sum_k \frac{|t_k - t_{k+1}|}{T} \tag{19}$$

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

$$\left| \frac{\sin(\pi t_k)}{\pi t_k} \frac{\cos(\pi \alpha t_k)}{1 - 4\alpha^2 t_k^2} \right| = \frac{i-1}{M} \tag{20}$$

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

$$\left| \frac{\sin(\pi t_{k+1})}{\pi t_{k+1}} \frac{\cos(\pi \alpha t_{k+1})}{1 - 4\alpha^2 t_{k+1}^2} \right| = \frac{i}{M} \tag{21}$$

The received power at a slot that a pulse is transmitted is [23]

$$y_{1i} = P\sqrt{\mathrm{LT}}[1 - \mathrm{ISR}(1 - s_i^n)] + \eta, \quad i = 1, \ldots, M \tag{22}$$

where $s_i^n = s_i/s_{\max}$ is the normalized quantized level and η is white Gaussian noise with zero mean and variance σ^2. The received power at slots where no pulse is transmitted is given by

$$y_{0i} = P\sqrt{\mathrm{LT}}\,\mathrm{ISR}(1 - s_i^n) + \eta \quad i = 1, \ldots, M \tag{23}$$

The conditional error probabilities for a 'pulse' and 'zero' slot in an L-PPM symbol are given by

$$p_{e1} = \sum_{i=1}^{M} p_i \mathsf{Q}\left(\frac{t_\mathrm{n} - P\sqrt{\mathrm{LT}}(1 - \mathrm{ISR}(1 - s_i^n))}{\sigma}\right) \tag{24}$$

$$p_{e0} = \sum_{i=1}^{M} p_i \left(1 - \mathsf{Q}\left(\frac{t_\mathrm{n} - P\sqrt{\mathrm{LT}}(\mathrm{ISR}(1 - s_i^n))}{\sigma}\right)\right) \tag{25}$$

where t_n is the normalized threshold and $\mathsf{Q}(x)$ is the standard error function defined as

$$\mathsf{Q}(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} \mathrm{e}^{-(x)^2/2}\, \mathrm{d}x \tag{26}$$

As an error in the 'pulse' slot is more important than an error in a 'zero' slot in L-PPM modulation, $t_\mathrm{n} = 0.3P\sqrt{\mathrm{LT}}(1 + \mathrm{ISR}_M)$ is used because it provides a small p_{e1} probability [21,23]. Note that SNR can be defined as $\mathrm{SNR} = 10\log((P\sqrt{\mathrm{LT}})^2/\sigma^2)$.

If a symbol is repeated RR times, the receiver implements L counters to track the number of received pulses in every symbol slot. If the counter of the slot that the pulse is originally placed has the maximum value, the symbol is captured successfully. Otherwise, the symbol is not captured successfully and a packet error occurs. The probability that 'pulse' slot counter has RR-i pulses is given by

$$\Phi_i^1 = \binom{\mathrm{RR}}{i}(1 - p_{e1})^{\mathrm{RR}-i} p_{e1}^i \tag{27}$$

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

$$\Phi_j^0 = \binom{\mathrm{RR}}{j}(1 - p_{e0})^j p_{e0}^{\mathrm{RR}-j} \tag{28}$$

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

$$\Phi^{L-1} = \left(1 - \sum_{j=0}^{i} \Phi_j^0\right)^{L-1} \tag{29}$$

and the successful symbol capture probability can be evaluated as

$$P_{\mathrm{sc}} = \sum_{i=0}^{\mathrm{RR}-1}\left[\Phi_i^1\left(1 - \sum_{j=0}^{i} \Phi_j^0\right)^{L-1}\right] \tag{30}$$

Finally, the packet error rate, p_e, is given by

$$p_e = 1 - P_{\mathrm{sc}}^{l/\log_2 L} \tag{31}$$

Figure 13 plots utilization and PER versus SNR for all proposed RR values for $l = 2048$ bytes, $\mathrm{ISR} = 10\%$, $t_\mathrm{n} = 0.3$, $\alpha = 0.75$ and $M = 16$. These parameter values are selected

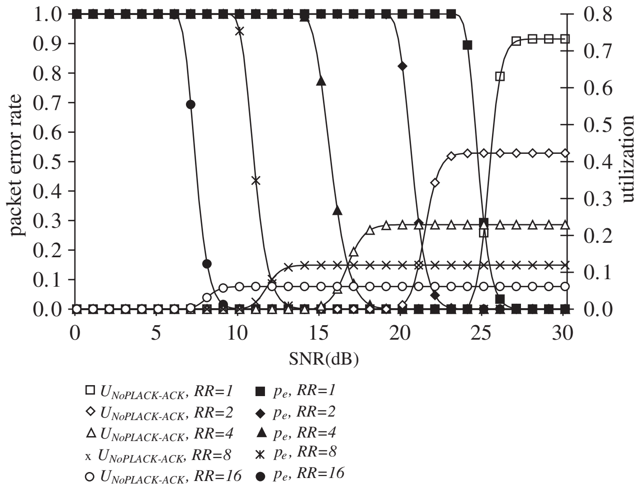

Figure 13. Utilization and packet error rate versus *SNR* for various *RR* values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $w = 8$ packets, $ISR = 10\%$, $t_n = 0.3$, $\alpha = 0.75$, $M = 16$.

in the literature for the modelling of AIr protocol as they provide analysis results that correspond to AIr prototyping outcome [4, 13, 23]. It shows that doubling RR provides approximately a 3–4 dB SNR gain in PER. Reducing SNR results in a higher PER. Doubling RR results in a very low PER and an LAN utilization very close to half of the original utilization. When should the transmitter double the RR it implements to achieve maximum utilization? Figure 14 plots the maximum NoPLACK-ACK utilization and the corresponding PER versus SNR when RR is adjusted to the value that results in maximum utilization for the specific SNR. The peaks in PER show that if PER increases, RR should be doubled to avoid utilization drop. Figure shows that RR should be adjusted if PER is greater than approximately 0.1. The receiver should monitor link quality and if the PER it calculates is greater than 0.1, it should advice the transmitter to double the RR it implements. Figure 15 plots the same results for the PLACK-M protocol. It shows that the PER value at which RR should be adjusted is increased to approximately 0.4. As a conclusion the PER value at which RR should be adjusted for maximum utilization depends on the utilized ARQ protocol.

Figure 16 plots utilization versus SNR for various RR values for NoPLACK-ACK and PLACK-M protocols. It shows that PLACK-M always achieves a higher utilization for the same RR because the utilized window size of four packets is less than the critical value of 8, a conclusion drawn in Section 4. Figure 16 also shows that if the RR is increased, the link reaches a considerable utilization even for low SNR values. The RR should be increased if the link distance results in a low SNR value. Figure 17 plots the same results for a window size of 16, a value greater than the 'critical' value of 8. In this case, NoPLACK-ACK outperforms PLACK-M protocol for high SNR values. However, as SNR lowers and before the point is reached when the RR for the PLACK-M protocol should be doubled, PLACK-M achieves a higher utilization. The situation is explained by considering that for large window sizes, the NoPLACK-ACK protocol is very sensitive to error rate increase caused by lower SNR values. When a large window size is implemented, the transmitter should select the suitable protocol

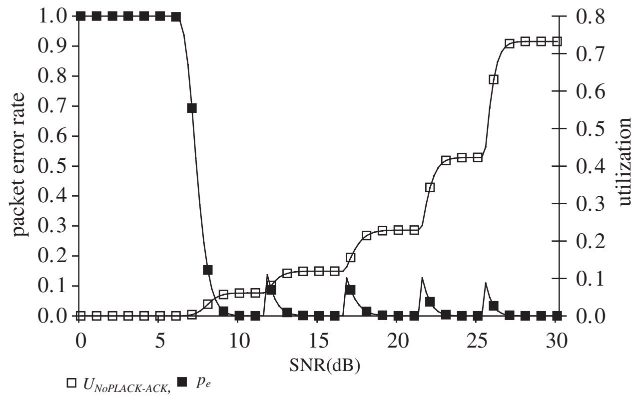

Figure 14. Utilization and packet error rate versus *SNR* for *RR* adjustment, $C_p = 2.8$ ms, $T_t = 5$ s, $C = 4$ Mbit/s, $l = 2$ Kbytes, $w = 8$ packets, $ISR = 10\%$, $t_n = 0.3$, $\alpha = 0.75$, $M = 16$.

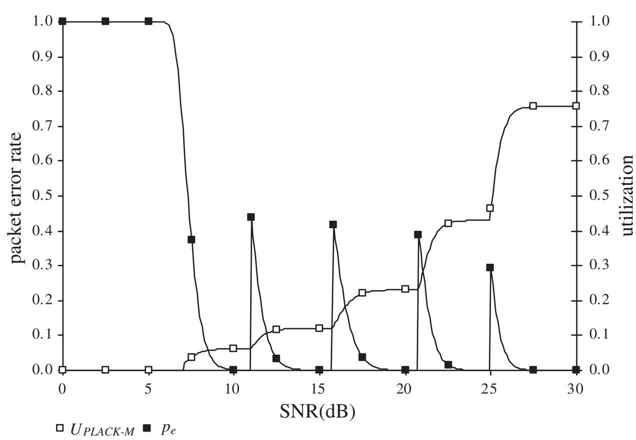

Figure 15. Utilization and packet error rate versus *SNR* for *RR* adjustment, $C_p = 2.8$ ms, $T_t = 5$ s, $C = 4$ Mbit/s, $l = 2$ Kbytes, $w = 8$ packets, $ISR = 10\%$, $t_n = 0.3$, $\alpha = 0.75$, $M = 16$.

and RR value simultaneously in order to achieve the highest possible utilization for a specific SNR value.

6. CONCLUSIONS

This paper has examined design issues of the GBN at the LC layer and of the SW at the MAC layer ARQ protocols for wireless infrared LANs. Analytical models for several protocol design cases for the AIr protocol standard are developed. Models are employed to explore LAN utilization for various parameter values such as window size and packet length under varying error rates. Results indicate that if the optional MAC SW ARQ scheme is not employed, the

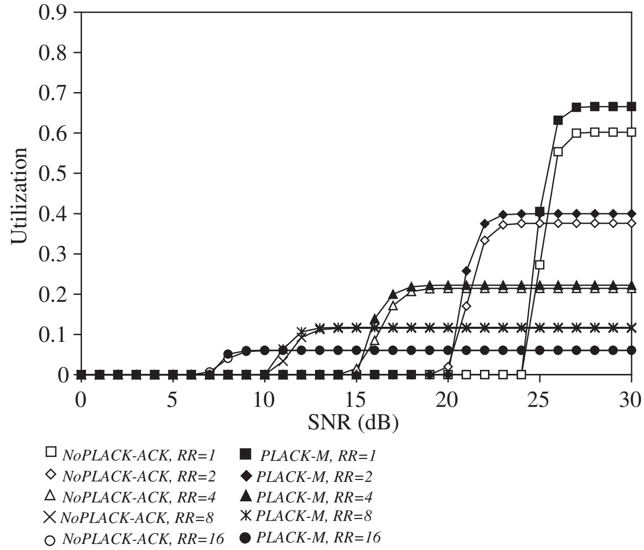

Figure 16. Utilization versus *SNR* for various *RR* values, $C_p = 2.8\,\text{ms}$, $T_t = 5\,\text{s}$, $C = 4$ Mbit/s, $l = 2$ Kbytes, $w = 4$ packets.

transmitter should always set the P/F bit in an LC ACK packet and not in a DATA packet. The reason is that the time required for the additional ACK packet transmission is very small compared to other protocol delays, such as TAT delays and control frame transmissions. If the P/F bit is set in the last DATA packet in a window transmission, utilization may strongly degrade when error rate increases and only a few stations are transmitting in the LAN. Results also indicate that if the optional SW ARQ scheme at the MAC layer is used, the LC layer should not implement its GBN ARQ scheme because the delay caused by the additional LC ACK packet transmissions is significant as it involves additional RTS/CTS transmissions and TAT delays.

Infrared LANs achieve high utilization only when high window and packet size values are employed at low error rates. Otherwise, utilization significantly degrades due to time utilized in transmitting packet overheads, reservation control packets (RTS, CTS, EOB, EOBC), contention periods and TAT delays. For small window sizes, MAC layer's SW ARQ scheme is preferable than LC layer's GBN scheme for higher utilization. The reason is that in this case MAC ACK packets take less time than the LC layer's ACK packet. The situation is reversed for window sizes higher than a 'critical' value, where LC layer's GBN scheme achieves a higher utilization. The 'critical' window size value depends on the average contention period, which is a function of the number of the transmitting stations in the LAN. However, LC GBN is sensitive to error rate increase and is not an efficient choice for links expected to experience high error rates. MAC layer's SW ARQ scheme is robust to error rate increase and should always be implemented in links experiencing high error rates.

Infrared LANs also employ RR coding to cope with low SNR at the receiver. RR coding is very effective in *L*-PPM links when the receiver is far away from the transmitter and has a low SNR value. It is concluded that the error rate at which RR adjustment is beneficial depends on the implemented ARQ protocol. If PER is higher than 0.12 for the NoPLACK-ACK protocol

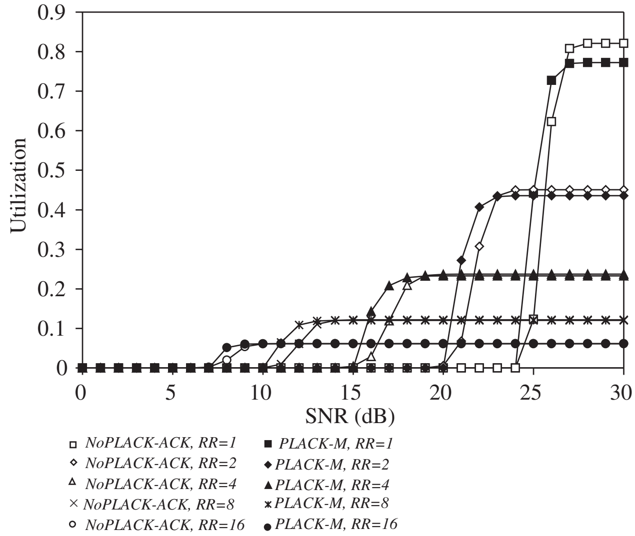

Figure 17. Utilization versus *SNR* for various *RR* values, $C_p = 2.8$ ms, $T_t = 5$ s, $C = 4$ Mbit/s, $l = 2$ Kbytes, $w = 16$ packets.

and higher than 0.4 for the PLACK-M protocol, the receiver should advise the transmitter to double the implemented RR in order to achieve maximum utilization. These PER values are high and can be effectively estimated by the transmitter. Thus, the usefulness of the receiver's indications concerning RR adjustment is questionable.

Results also indicate that when the implemented window size is small, MAC layer's SW ARQ scheme is always the best choice and the transmitter should only select the suitable RR value for the specific link quality. However, when the implemented window size is high, maximum utilization is achieved for a specific SNR when the transmitter implements the suitable ARQ and RR value simultaneously.

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