A COMPARISON OF STOP-AND-WAIT AND GO-BACK-N ARQ SCHEMES FOR IEEE 802.11e WIRELESS INFRARED NETWORKS

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A Comparison of Stop-and-Wait and Go-Back-N ARQ Schemes for IEEE 802.11e Wireless Infrared Networks

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Abstract - **The upcoming IEEE 802.11e standard adds a new optional acknowledgment scheme, which is called Burst Acknowledgment (BurstAck) in order to support Quality of Service (QoS) and better utilization of the wireless medium (WM). In this paper the efficiency of the well-known Stop-and-Wait (SW) mechanism and the enhanced Burst Acknowledgment (BurstAck) behavior, utilized as a Go-Back-N (GBN) Automatic Repeat Request (ARQ) scheme with Sliding Window is studied. Link parameters such as, the window size of the transmitted MAC protocol data units (MPDUs), the number of stations, (STAs) the frame error rate (FER) and the signal to noise ratio (SNR) are considered. In our analysis, the specific characteristics of the infrared physical layer as well as the 802.11 Management Information Base (MIB) parameters for infrared wireless LANs and the complex behavior of 802.11 MAC protocol are taken into account. The results obtained indicate that BurstAck utilized as GBN performs better for medium sized networks with large window size and not very high FER. However, for small window size, bad channel quality and large networks the GBN scheme is not suggested.**

Index Terms - Keywords: **IEEE 802.11, SW, GBN, Burst Acknowledgment.**

1. INTRODUCTION

The stations (STAs) in infrared (IR) Wireless Local Area Networks (WLANs) according to the IEEE standard transmit in a fixed wavelength from 850-950 nm [1]. Infrared radiation is reflected by indoor environment surfaces, which are nor dark or transparent [2, 3]. IR radiation propagates through multiple reflections and as result a system similar to radio in terms or coverage area is established. As a consequence full mobility of STAs is provided [4, 5]. IR WLANs are preferable in places where the interference produced must be avoided (e.g. airplanes, airports, ships, conference halls, etc.). IR WLANs provide wireless connectivity and support purely cellular architecture [4, 5], which makes them advantageous in covering large indoor spaces. Moreover, optical wireless communication systems can be candidates for Wireless Home Link (WHL) since they can provide high-speed communication between home devices and are unlicensed.

However, IR has several drawbacks. Multi-path dispersion, which is related to the time dispersion of the received pulse, is observed as inter symbol interference (ISI) to the receiver for transmission rates higher than 10 Mbps [3, 5, 6, 7]. In the case of IEEE 802.11 the IR links have transmission rate 1 and 2 Mbps and those phenomena are avoided. Another drawback of the IR link is that ambient light provokes shot noise, due to the random nature of the photo-detection process, while artificial light provokes interference due to light intensity periodic variations [8, 9]. For low and moderate rates as in the case of IEEE 802.11, the ambient noise is the major factor degrading the wireless infrared link performance [8, 9].

It is common to use for the transmission over infrared medium intensity modulation (IM) for the transmitter and direct detection (DD) for the receiver. The signal-to-noise ratio (SNR) is proportional to the square of the received optical power when a DD receiver is used, while in radio transmission it is proportional to the received power. Thus, high levels of optical power must be emitted due to shadowing and ambient noise, which is not permitted by international safety regulations and by power consumption constraints of STAs. Therefore, the transmitted signal must be processed to allow its detection with the lowest possible signal-to-noise ratio. Pulse position modulation (PPM) is adopted by the IEEE 802.11 standards [1] as the transmission technique that offers the best transmission characteristics for this type of transmission channel [9]. Recently, due to the increased demand for multimedia applications on mobile/portable devices, an enhanced version of the IEEE 802.11 standard has been developed [10] to support differential services and quality of service (QoS). One of the features of the new version is the optional acknowledgment scheme, known as Burst acknowledgement (BurstAck). The ARQ scheme performance has been previously addressed for radio transmission [11] and IR transmission [12, 13]. The performance of BurstAck utilized as a selective repeat (SRP) ARQ in the simple case of one transmitter and one receiver is studied in [14]. The more complicated case of arbitrary number of transceivers has been addressed in [15]. In [14, 15] the channel is released by an STA when the successful transmission of N packets, using sub sequenced bursts (with the same or decreasing window size), is completed.

In this work we assume a fixed MPDU size window, the wireless medium (WM) is released immediately after the end of a single burst, regardless if the packets have been transmitted successfully or not and the easier in implementation GBN ARQ scheme with sliding window is adopted. It is the aim of this work to analyze the performance of BurstAck, utilized as a Go-Back-N (GBN) Automatic Repeat Request (ARQ) with sliding window. More specifically, we compare the GBN ARQ scheme with the well known Stop-and-Wait (SW) ARQ utilized up to now in the IEEE 802.11 standards. In our analysis, we have taken into account the IR physical layer, but it is easy to switch to other physical layers taking into account their specific features. We assume saturation conditions (i.e. the maximum load that can be handled without loosing stability) and a finite number of STAs, in the network, which are contenting to access an IR erroneous channel to transmit a specific number (N) of MAC Protocol Data Units (MPDUs). The network uses the EDCF [16] access method and the request-to-send/clear-to-send (RTS/CTS) scheme being more effective (compared to the basic access scheme) when saturation conditions apply [17, 18]. Numerical results are presented for two cases: (a) all STAs use the SW acknowledgment scheme and (b) all STAs use the BurstAck mechanism. The efficiency of the acknowledgement scheme and the operating conditions are investigated.

The paper is organized as follows: In Section II the SW and BurstAck mechanisms are shortly described. The analysis and derivation of the infrared frame error rate (FER) is presented in Section III. In Section IV, the access delay of a MPDU is derived using the typical MIB parameters of the 802.11 MAC protocol for IR. In Sections V and VI, we analyze the average transmission delay for SW and GBN with sliding window. Numerical results and the comparison of SW and GBN performance are presented in Section VII. In Section VIII, the advantages and limitations of our analysis are presented.

Octets: 2	2	6	6	6	2	6	2	0-2312	4
Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	QoS Control	Frame Body	FCS

Figure 1. Enhanced MAC Frame.

TABLE 1. ACK POLICY SUB-FIELD OF QOS FIELD

Bit 10	Bit 11	Meaning
0	0	Normal IEEE 802.11 acknowledgement
0	1	Reserved
1	0	No Acknowledgement
1	1	Burst Acknowledgement

2. IEEE 802.11E ACKNOWLEDGMENT SCHEMES

The 802.11e MAC protocol [16] supports three types of acknowledgment (see Table 1), through a modification of the MAC frame. A new field called Quality of Service (QoS) is used with a subfield called Acknowledgment (ACK) Policy field (Fig.1). This field can be defined by the bit values presented in Table 1. There is the possibility to use either SW or BurstAck or even no acknowledgment mechanism. The latter is used when the channel quality is extremely high and the non-delivery of some MPDUs such as in voice transmission is not vital as far as the packet delay does not exceed some predefined delay constraints.

2.1. Stop and Wait

In the well-known SW ARQ scheme, the transmitter initially, contends with the rest STAs of the network to capture the WM and after a successful reservation sends an RTS frame. Once the RTS frame is received, the receiver responds with a CTS frame after a short inter-frame space (SIFS) time duration. Then, the transmitter sends a single MPDU and the receiver acknowledges with an ACK frame after SIFS duration if the MPDU has been received by the receiver, without errors.

If the MPDU is corrupted then there is a lack of the expected ACK frame (the transmitter waits more than SIFS) indicating to the transmitter that an error occurred. Note, that the receiver may have received the frame correctly, and that the error may have occurred in the reception of the ACK frame. However, to the transmitter of the frame exchange, this condition is indistinguishable from an error occurring in the initial frame.

After a corrupted MPDU the transmitter resends the MPDU following the same procedure. Failed transmissions for the same MPDU increment the retry limit associated with that MPDU, and is reset when this MPDU is successfully transmitted. If the retry limit is reached, the MPDU is discarded and its loss is reported to higher layer protocols. In 802.11a,b MAC protocol the Stations have two retry counters, the *short retry count* and the *long retry count*. Depending on the length of the frame, the MPDU is associated with either a short or a long retry counter. Indeed, frames that are shorter than the RTS threshold are considered to be short while frames longer than the threshold are considered long. Frames retry counts begin at 0 and are incremented when a frame transmission fails. The short retry count is reset to 0 when :

- A CTS frame is received in response to a transmitted RTS
- . A MAC –layer acknowledgement is received after a non fragmented transmission
- . A broadcast or multicast frame is received

The long retry count is reset to 0 when :

- . A MAC-layer acknowledgement is received for a frame longer than the RTS threshold
- . A broadcast or multicast frame is received

The short and long retry counters in 802.11 which correspond to non-fragmented and fragmented transmission, respectively, are described in detail in Ref [1].

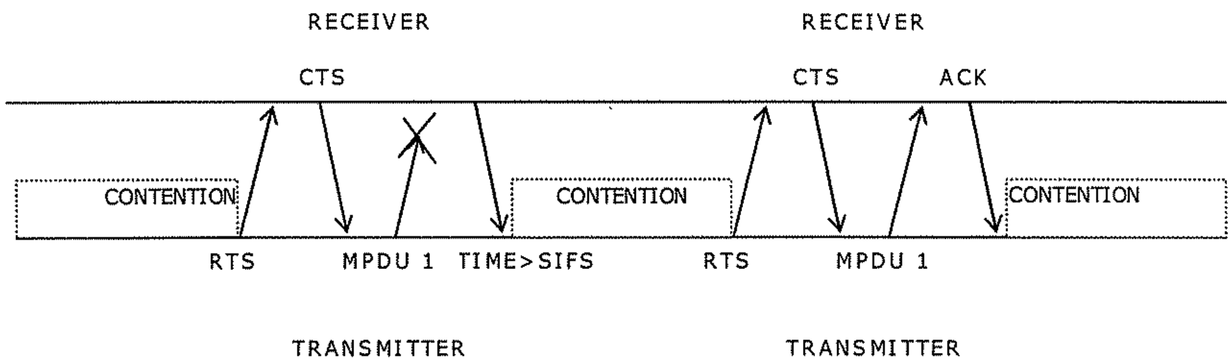

Figure 2. Schematic of Stop & Wait ARQ Scheme in 802.11 and 802.11e MAC Protocol.

2.2.Burst Acknowledgment utilized as GBN with sliding window

In the GBN with sliding window ARQ scheme, the transmitter keeps sending packets but keeps a copy in a buffer, which is called the transmission window. The number of packets in the buffer, or the window, is N which equals the number of packets sent during one round-trip time. If a corrupted MPDU arrives at the receiver (assume that it has a sequence number i), the receiver discards this MPDU and the MPDUS with sequence numbers $i+1, i+2, \ldots N$. Afterwards, it informs the transmitter until which MPDUs in sequence has been received successfully. Then, the transmitter forms a new window of N MPDUs which consists of the discarded MPDUS with sequence numbers *i*, *i+1,i+2,...N*, plus *i-1* new ones, (see Fig.3).

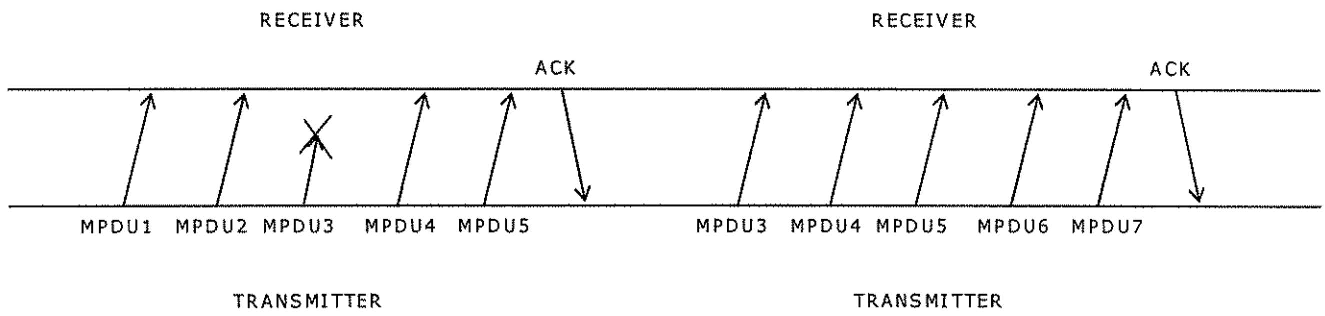

Figure 3. Schematic of GBN ARQ Scheme with sliding window (window size=5).

The BurstAck mechanism of 802.11e [10] utilized as a GBN ARQ scheme with sliding window, follows the RTS/CTS frame exchange method (Fig.4) as in SW. However, the data transmission in 802.11e is accomplished in three phases: (a) The setup phase, (b) the data and burst phase, and (c) the tear down phase. The setup phase is the initialization through the exchange of Define BurstAck Request (DFBARQ) and Define BurstAckResponse (DFBARS) frames between the transmitter and the receiver. Once the initialization is completed the data and burst phase starts. During this phase, the transmitter allows a burst (window N) of quality of service MPDUs to be transmitted separated by a SIFS time duration. When the transmitter wishes to get an acknowledgment for the already sent MPDUs, it transmits a BurstAck Request (BARQ) and waits for a BurstAck Response (BACK). Two types of BurstAck mechanisms exist: (a) the immediate (for low latency traffic which is also adopted in this paper), and (b) the delayed (moderate latency traffic). The tear down phase defines the end of the transmission and this can be done using an exchange of Delete Burstack Request (DLBARQ) and ACK frames.

The receiver discards the first corrupted MPDU and the following MPDUs of the burst. The receiver sending the BurstAck Response (BACK) frame informs the transmitter for the last successfully received MPDU and the corrupted MPDUs are retransmitted together with new ones (forming a window N) during the next burst. If the retry limit associated with a specific MPDU or Burst is reached then this MPDU or Burst is discarded and its loss is reported to the higher layer protocols. More specifically, in 802.11e MAC protocol every Quality of Service Station (QSTA) maintains a short retry counter and a long retry counter for each MAC service data unit (MSDU) or MAC management protocol data unit (MMPDU) that belongs to a traffic category (TC) requiring acknowledgement. Initially the values of for the short and long retry counters must be zero. The short retry counter for an MSDU or MAC management protocol data unit (MMPDU) increases each time transmission of a MAC frame of length less than or equal to RTS threshold fails for that MSDU or MMPDU. This short retry count must be reset when a MAC frame of length less than or equal to RTSThreshold succeeds for that MSDU or MMPDU. The long retry counter for an MSDU or MMPDU increases each time transmission of a MAC frame of length greater than RTSThreshold fails for that MSDU or MMPDU. This long retry counter must be reset when a MAC frame of length greater than dot11RTSThreshold succeeds for that MSDU or MMPDU. The short and long retry counters in 802.11e which correspond to non-fragmented and fragmented transmission respectively are described in detail in Ref [10].

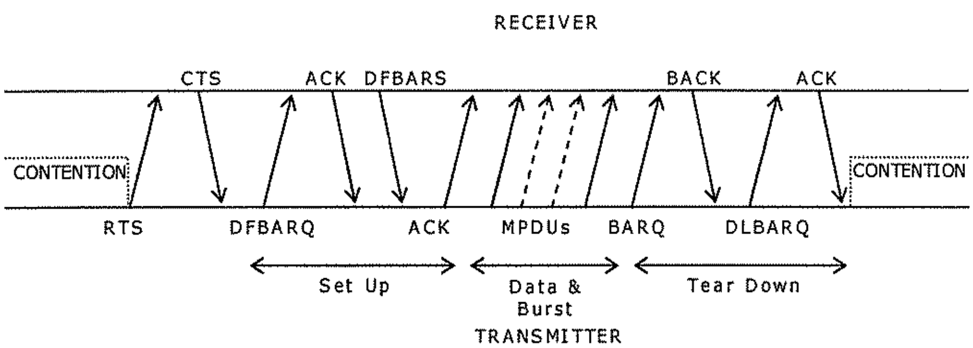

Figure 4. BurstAck Mechanism.

3. ANALYSIS OF INFRARED FRAME ERROR RATE

Considering an Additive White Gaussian Noise (AWGN) channel without optical interference and ignoring thermal noise, as specified in the IEEE 802.11 IR PHY section [1], the FER of the IR frame, can be derived [8, 9] for different channel conditions. FER can be written as:

$$FER = 1 - P_{SYNC} P_{SDF} P_{DR} P_{LENGTH} P_{CRC} P_{MPDU}, \tag{1}$$

where P_{SYNC}, P_{SDF}, P_{DR}, P_{LENGTH}, P_{CRC} and P_{MPDU} are the probabilities of the SYNC, SDF, DR, LENGTH, CRC and MPDU fields (Fig.5) to be correctly detected. The first three fields of the IR frame are transmitted using 4Mbps on-off-keying (OOK) non-return-to-zero (NRZ) modulation scheme. The other fields are using either 4PPM or 16PPM corresponding to 2Mbps and 1Mbps transmission rates, respectively. The BER is different for these two groups of fields, however, the same optical peak power is used in both OOK and PPM schemes. The BER for OOK NRZ transmission is given as:

$$BER_{OOK} = \frac{1}{2} Erfc\left(\frac{v_T}{\sqrt{2} \cdot \sigma_T}\right), \tag{2}$$

where $Erfc(x)$ is the complementary error function:

$$Erfc(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \tag{3}$$

and σ_T, v_T are the amplitudes of the noise and the signal at the sampling instant respectively ($\sigma_T = \sqrt{q \cdot I_B \cdot 1/T_{PS}}$ and $v_T = R \cdot P_{AVR}$). I_B is the current to the receiver due to ambient light, T_{PS} is the pulse slot duration, P_{AVR} is the average received optical power, R is the photodiode responsivity and q is the electron charge.

The BER for L-PPM assuming a simple threshold receiver is given as:

$$BER_{PPM} = \frac{2^{k-1}}{2^k - 1} \cdot \left[1 - \left(\frac{1}{L} P_{01} (1 - P_{10})^{L-1} + \sum_{n=1}^{L} \frac{1}{n} \binom{L-1}{n-1} (1 - P_{01}) P_{10}{}^{n-1} (1 - P_{10})^{L-n} \right) \right], \tag{4}$$

where $L = 2^k$ is the number of distinguished symbols that can be transmitted using the L-PPM modulation technique and k is the number of bits per symbol. P_{01} and P_{10} are the probabilities of non-detection of a transmitted pulse and of detection of a pulse not transmitted, respectively. Those are equal if the threshold level is half the peak level at the sampling instant:

$$P_{01} = P_{10} = \frac{1}{2} Erfc\left(\frac{L v_T}{2\sqrt{2} \cdot \sigma_T} \right), \tag{5}$$

Details on P_{SYNC}, P_{SDF}, P_{DR}, P_{LENGTH}, P_{CRC} and P_{MPDU} can be found in [8, 9].

SYNC	SFD	DR	DCLA	Length	CRC	MPDU
57-73 slots	4 slots	3 slots	32 slots	16 bits	3 bits	0-1500 bits

Figure 5. IEEE 802.11 Infrared Frame.

4. ANALYSIS OF 802.11 MAC ACCESS DELAY

Denote as D, the delay between the time an STA has a frame ready to transmit and the time that the STA has captured the medium and is ready to transmit successfully (without collisions) over the WM. $E[D]$ is the mean value of D which is calculated following [18]. $E[D]$ is expressed as:

$$E[D] = E[N_c](E[BD] + T_c + T_o) + E[BD], \tag{6}$$

where $E[N_c]$ is the average number of collisions that an STA experiences until the successful reservation of the WM and T_o represents the time that an STA has to wait, when its frame collides, before sensing the medium again. $E[N_c]$ can be written as:

$$E[N_c] = \frac{1}{P_s} - 1, \tag{7}$$

where P_s is the probability for a collision-free transmission. T_o depends on the access method used, and for RTS/CTS is given as:

$$T_o = T_{SIFS} + T_{CTS\_timeout}, \tag{8}$$

where T_{SIFS} is the time interval between two sequential frame transmissions, $T_{CTS\_timeout}$ is the maximum time that an STA waits for a CTS response and T_c is the time interval that the channel is sensed busy due to a collided transmission. T_c depends on the access method used and for RTS/CTS is:

$$T_C = T_{RTS} + T_\delta + T_{AIFS}, \tag{9}$$

where T_{RTS} is the time required for the transmission of the RTS frame including the overhead of the physical layer, T_δ is the frame propagation delay and T_{AIFS} is the time interval that an STA senses the medium in order either to transmit or to decrease its backoff counter [16].

The average backoff delay, $E[BD]$, which is the average time that an STA has to wait after choosing a random slot before accessing the channel under busy channel conditions is given as:

$$E[BD] = E[X] + E[F], \tag{10}$$

where

$$E[X] = \sum_{j=0}^{m} \sum_{k=1}^{W_j - 1} k b_{j,k}, \tag{11}$$

and

$$E[F] = E[N_F](P_s T_s + (1 - P_s) T_c). \tag{12}$$

To derive equation (11) a Markov chain model has been used [18]. $E[X]$ is the mean value of a random interval, corresponding to k slots needed by the counter to reach slot $k = 0$, $b_{j,k}$ is the probability for slot k to be in backoff stage j, m is the maximum number of backoff stages and W_j the window size in the backoff stage j. F is the time period the counter of an STA freezes which depends on the transmission success and $E[N_F]$ is the average number of times that the counter freezes, given as:

$$E[N_F] = \frac{E[X]}{\max(E[\Psi],1)} - 1, \tag{13}$$

where $E[\Psi]$ is the average number of consecutive time slots before a transmission starts:

$$E[\Psi] = \frac{1}{P_b} - 1. \tag{14}$$

P_b in equation (14) is the probability for an STA to sense the medium busy and T_S in Equation (12) is the time interval that the medium is sensed busy by an STA when a successful transmission occurs. This interval depends on the access technique used and on the type of the acknowledgment scheme. When RTS/CTS is used and SW is implemented:

$$\begin{aligned} T_S^{SW} = {} & T_{RTS} + T_\delta + T_{SIFS} + T_{CTS} + T_\delta + T_{SIFS} + \\ & T_{MPDU} + T_\delta + T_{SIFS} + T_{ACK} + T_\delta + T_{AIFS} \end{aligned}. \tag{15}$$

When the BurstAck mechanism is used, then:

$$\begin{aligned} T_S^{BURST} = {} & T_{RTS} + T_\delta + T_{SIFS} + T_{CTS} + \\ & T_\delta + T_{SIFS} + T_{DFBARQ} + T_\delta + \\ & T_{SIFS} + T_{ACK} + T_\delta + T_{SIFS} + \\ & T_{DFBARS} + T_\delta + T_{SIFS} + T_{ACK} + \\ & N(T_{MPDU} + T_{SIFS}) + T_{BARQ} + T_\delta + \\ & T_{SIFS} + T_{BACK} + T_\delta + T_{SIFS} + \\ & T_{DLBARQ} + T_\delta + T_{SIFS} + T_{ACK} + T_{AIFS} \end{aligned} \tag{16}$$

T_{CTS}, T_{ACK}, T_{DFBARQ}, T_{DFBARS}, T_{BARQ}, T_{BACK}, T_{DLBARQ} are the time required for the transmission of the CTS, ACK, DFBARQ, DFBARS, BARQ, BACK DLBARQ frames, respectively. T_{MPDU} is the transmission time for the MPDU. For simplicity, we assume that only one EDCF Access Category (AC) is implemented in every STA and consequently the same parameters with DCF over IR, are used. As a result $E[D]$ depends on the number of STAs, the MPDU size and the transmission rate.

5. ANALYSIS OF THE SW ARQ SCHEME

The probability P_i for the transmitter to send i MPDUs in order to N of them to be received correctly by the receiver is given as:

$$P_i = C_{i-1,N-1}(1-P_E)^N (P_E)^{i-N}, \tag{17}$$

where

$$C_{i-1,N-1} = \binom{i-1}{N-1} = \frac{(i-1)!}{[(i-1)-(N-1)]!(N-1)!}. \tag{18}$$

and P_E is the frame error rate (FER) of the MPDU.

Assuming that the small frames RTS, CTS and ACK are error free, the average time, which is needed to transmit N correct MPDUs, is given as:

$$T_{SW} = \sum_{i=N}^{\infty}\binom{i-1}{N-1}(1-P_E)^N (P_E)^{i-N} i(T_D + T_1), \tag{19}$$

where

$$T_1 = T_{RTS} + T_\delta + T_{SIFS} + T_{CTS} + T_\delta + T_{SIFS} + T_{MPDU} + T_\delta + T_{SIFS} + T_{ACK} + T_\delta + T_{AIFS}, \tag{20}$$

and T_D is the average delay $E[D]$ for the SW scheme.

Equation (19) can be written as:

$$T_{SW} = \frac{N}{1-P_E}(T_D + T_1). \tag{21}$$

6. ANALYSIS OF GBN ARQ SCHEME WITH SLIDING WINDOW

We define $P_{n,i}$ as the probability for the transmitter to transmit successfully N distinguished MPDUS which consist the first created window, using n bursts (windows with N MPDUs) with i MPDUs out of the first N to be transmitted during the last (n^{th}) window. The erroneous MPDUs in each window are discarded by the receiver and retransmitted at the next window, and they do not affect the analysis and as a result simple combinatorics can be used to compute the probability $P_{n,i}$, when BurstAck is utilized as GBN ARQ scheme with sliding window:

$$P_{n,i} = C_{N-i+n-1,n-1}(1-P_E)^N (P_E)^n. \tag{22}$$

Assuming that all the frames involved in the BurstAck mechanism, except the MPDU frames, are error free transmitted, the average time, which is needed to transmit N correct MPDUs, is given as:

$$T_{GBN} = P_{1,0}(T_D + T_W) + \sum_{n=1}^{\infty} \sum_{i=1}^{N} \Big\{ P_{n,i} \times \\ [n(T_D + T_W + T_{WE}) + (T_D + i(T_{MPDU} + T_{SIFS}))] \Big\} \tag{23}$$

Equation (23) results into the following closed form:

$$\begin{aligned} T_{GBN} &= (1 - P_E)^N (T_D + T_{SE} + T_W) + \\ &+ \frac{P_E N}{1 - P_E}(T_D + T_{SE} + T_W + T_{TD}) + \\ &+ \frac{1 - P_E - (1 - P_E)^{N+1}}{1 - P_E}(T_D + T_{SE}) + \\ &+ \frac{1 - P_E - (1 - P_E)^{N+1}(1 + P_E N)}{1 - P_E}(T_{MPDU} + T_{SIFS}) \end{aligned} \tag{24}$$

Here, T_D is the average delay $E[D]$ for the BurstAck scheme and T_{SE} is the time required for a successful transmission of the start up phase:

$$\begin{aligned} T_{SE} &= \\ & T_{RTS} + T_\delta + T_{SIFS} + T_{CTS} + T_\delta + T_{SIFS} + T_{DFBARQ} + \\ & T_\delta + T_{SIFS} + T_{ACK} + T_\delta + T_{SIFS} + T_{DFBARS} + T_\delta + \\ & T_{SIFS} + T_{ACK} + T_{AIFS}. \end{aligned} \tag{25}$$

T_{TD} is the overhead introduced during the tear down phase.

$$\begin{aligned} T_{TD} = T_{BARQ} + T_\delta + T_{SIFS} + T_{BACK} + T_\delta + T_{SIFS} + \\ T_{DLBARQ} + T_\delta + T_{SIFS} + T_{ACK} \end{aligned}, \tag{26}$$

T_W is the overhead introduced due to physical layer, MAC layer and SIFS durations for a window of N packets, as well as the transmission time for N packets:

$$T_W = N(T_{SIFS} + T_{MPDU}). \tag{27}$$

7. RESULTS

We assume MPDU size 512 bytes, OOK transmitted bit rate 4Mbps and PPM transmitted bit rate for the MPDU 1Mbps. The latter is low enough to ignore ISI effects due to multi-path effects [3]. We use a simple PPM threshold receiver with negligible front-end noise. Thus, the noise produced at the receiver is dominated mainly by the ambient light [8]. Note also, that the presented values of SNR of the transmitted IR pulse refer to the electrical SNR. All the parameters of the system under discussion are shown in Tables 2 and 3.

TABLE 2. MIB AND SYSTEM PARAMETERS.

Symbol	Parameters	Value
R	Transmission Rate	1 Mbps
SIFS	SIFS Time	10×10^{-6} s
PL	Preamble Length	20×10^{-6} s
PLCP	PLCP Header Length	25×10^{-6} s
PHY	PHY Header	PL+PLCP
MAC	MAC Header	36×8 bits

TABLE 3. FRAMES USED FOR BURSTACK AND SW SCHEMES.

Symbol	Parameters	Value

DFBARQ	Define Burst Ack Request	6×8 bits
DFBARS	Define Burst Ack Response	6×8 bits
DLBARQ	Delete Burst Ack Request	6×8 bits
BACK	Burst Ack	152×8 bits
BARQ	Burst Ack Request	24×8 bits
MPDU	MPDU Size	512×8 bits
RTS	RTS length	20×8 bits
CTS	CTS length	14×8 bits
ACK	ACK length	14×8 bits

We use the following performance factor:

$$U = \frac{T_{GBN}}{T_{SW}} \tag{27}$$

The less the factor U, compared to unity is, the performance of GBN compared to SW is better. In Figs. 6-7, the performance factor U is plotted vs. the window size N for n=10 and n=20 respectively and various P_E. The performance of GBN is better as N increases when $P_E \leq 10^{-2}$. U is not significantly affected for $10^{-6} < P_E < 10^{-2}$ but this is not true for $10^{-2} < P_E < 10^{-1}$. When $10^{-2} < P_E < 10^{-1}$ the degradation of GBN is more evident for larger n (n=20) making the use of GBN impossible under these conditions.

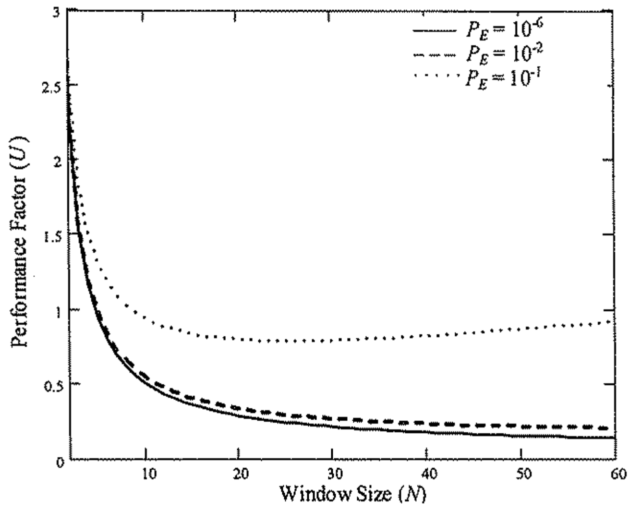

Figure 6. Performance Factor U vs N for n=10.

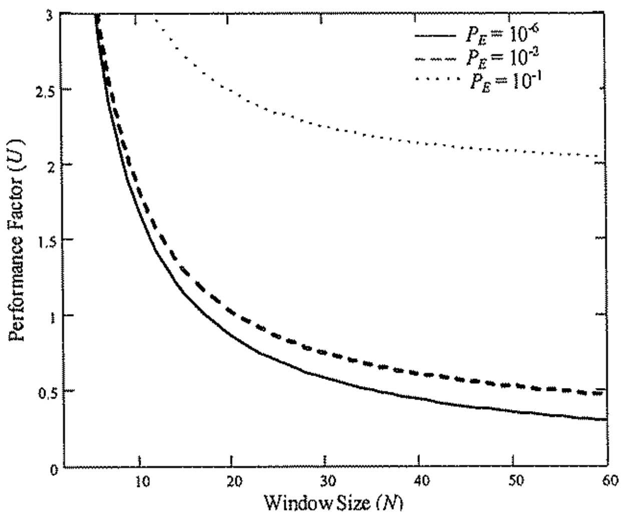

Figure 7. Performance Factor U vs N n=20.

In general, GBN efficiency improves compared to SW when N takes relatively high values and P_E is not extremely high. However, when n increases, larger windows must be used in order to achieve the same performance for the same P_E.

Figs. 8-9 show the relationship between the performance factor U and the number of STAs n, for N=20 and N=50. U increases almost linearly with n. The effect of P_E on U is negligible when P_E ranges from 10^{-6} - 10^{-2}. However, for values of $P_E > 10^{-2}$ a rapid degradation of GBN is observed. The effect is stronger in Fig. 8 where N is smaller (N=20). It is also observed that the efficiency of GBN is better than SW when N=20 and n<20 for $P_E = 10^{-1}$ or n<23 for $P_E = 10^{-2}$ and $P_E = 10^{-6}$, while in Fig. 9 the efficiency of GBN is better than SW when N=50.

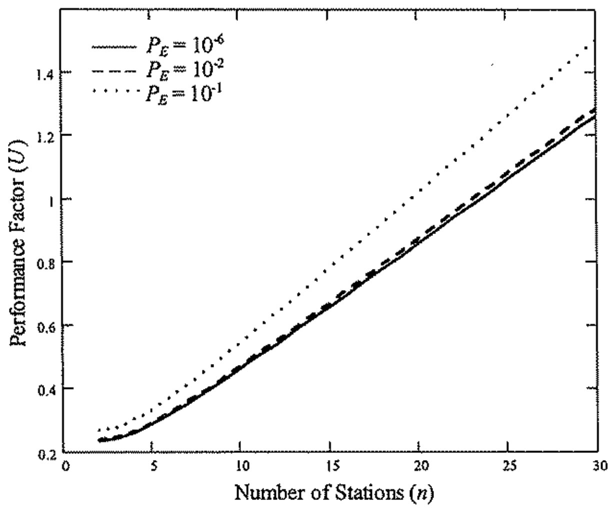

Figure 8. Performance Factor U vs n for N=20.

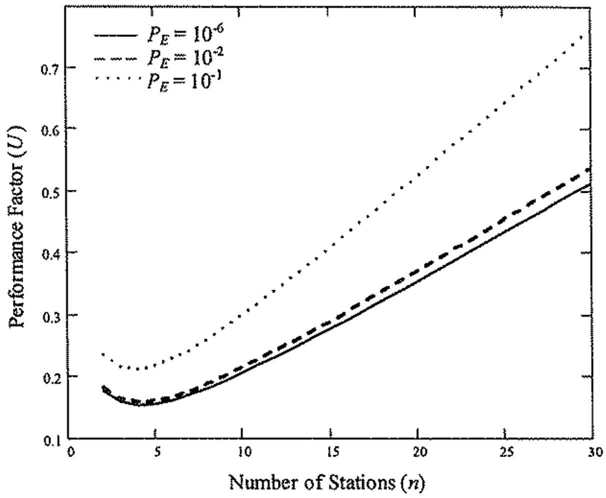

Figure 9. Performance Factor U vs n for N=50.

Figs. 10-11 show the dependence of factor U on the frame error rate P_E for N=20 and N=50. Each of the curves corresponds to a different n. Each curve can be divided in two regions. In the first region, U is not affected by P_E (P_E <10^{-2}). In the second region (P_E $\geq 10^{-2}$) the performance of GBN becomes worse rapidly compared to SW. In Fig. 10 GBN is better than SW even for high n when P_E<10^{-2}. However, in Fig. 10 the small window size makes GBN less efficient than SW when n is high (n=30) even for low P_E values.

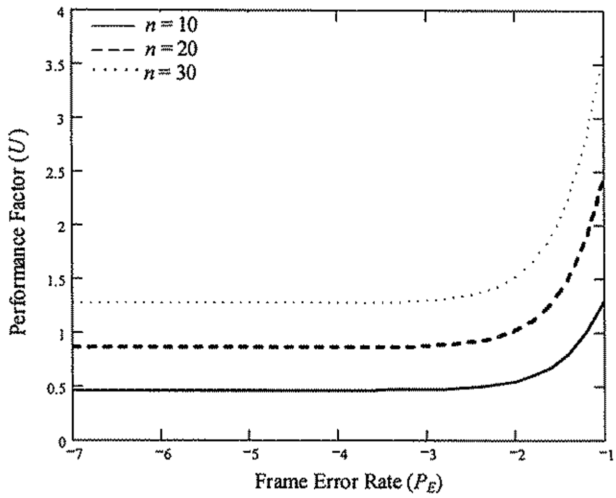

Figure 10. Performance Factor U vs P_E for N=20.

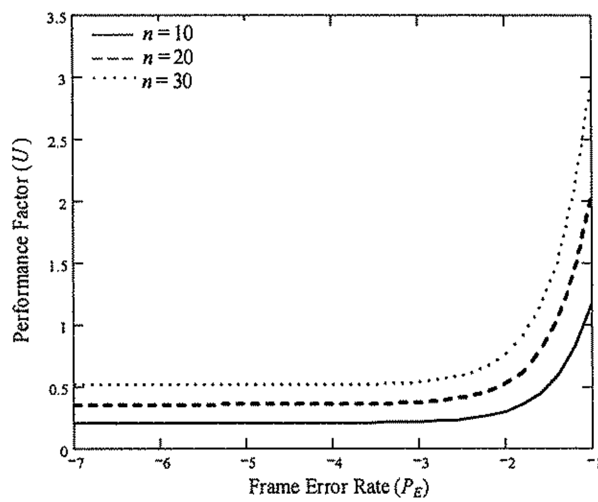

Figure 11. Performance Factor U vs P_E for N=50.

Figs. 12-13 show the dependence of U on the frame error rate P_E for n=10 and n=20, respectively. Each of the curves corresponds to a different window size N. For ($P_E \geq 10^{-2}$) the performance of GBN becomes worse compared to SW.

P_E vs N is shown in Fig. 14 when U=1 ($T_{SW} = T_{GBN}$). This constraint denotes that the time required for SW and GBN is the same for certain values of N, P_E and n. The points in the upper area of each curve imply that for certain values of N, P_E and n SW has better performance compared to GBN. The opposite is true for the points under the curve. Moreover, as the area under the curve increases the performance of GBN becomes better, since a higher value of P_E is required to force the performance of GBN to be equal of SW.

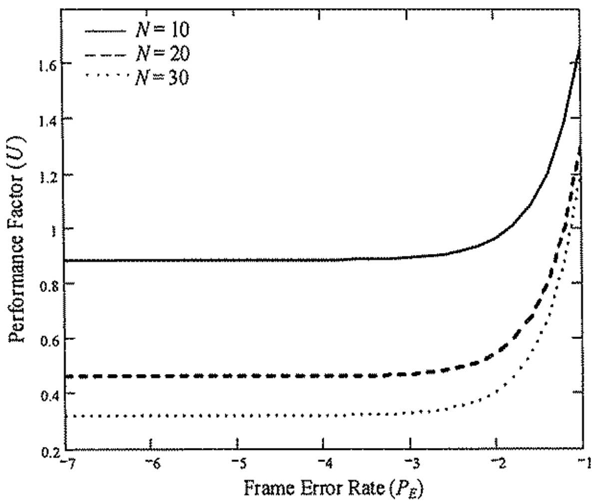

Figure 12. Performance Factor U vs P_E for n=10.

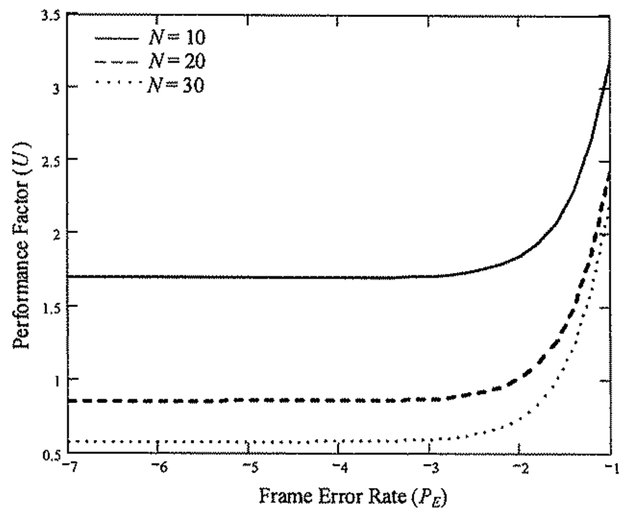

Figure 13. Performance Factor U vs P_E for n=20.

Fig. 14 is of practical importance for network designers to choose either SW or GBN as the candidate ARQ scheme employed. The only information that is required is the quality of the infrared channel, and N can be adjusted in order to fulfill the requirement for better channel efficiency using either SW or GBN.

In Fig. 15 P_E vs SNR is plotted for the channel conditions specified in the IEEE 802.11 MAC protocol [1]. This plot can relate U directly with the SNR of the IR channel. For different channels conditions, Fig.15 will be somehow different, but Figs. 6-14 are still valid.

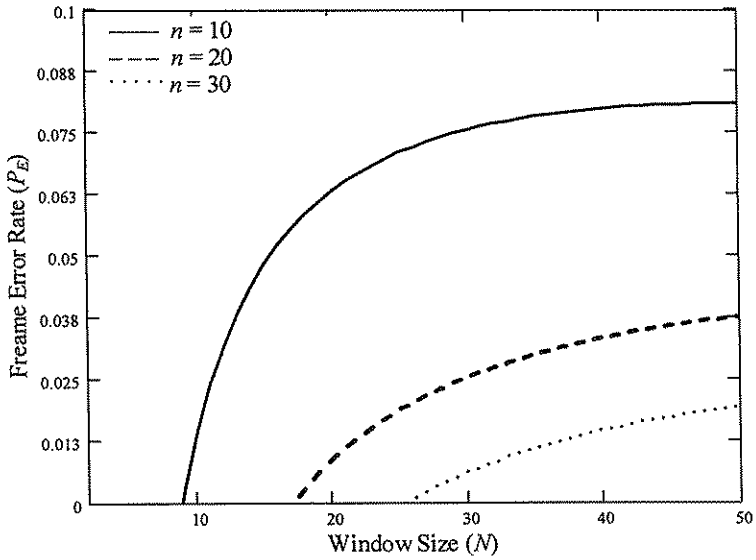

Figure 14. P_E vs N for different n under the constraint $T_{SW} = T_{GBN}$.

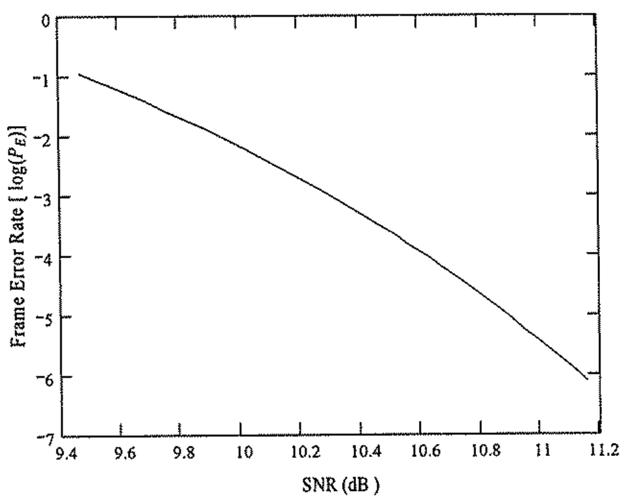

Figure 15. P_E vs SNR of the Infrared Pulse at the sampling time for the typical channel conditions (receiver sensitivity, background noise) assumed in 802.11 standard.

8. DISCUSSION

In this paper, we carried out a comparison between the well-known SW and the GBN ARQ scheme over IR 802.11 wireless networks. The presented analysis combined the features of the IR physical layer and the complicated behavior of the CSAMA/CA MAC layer in order to examine in detail the presented ARQ schemes. These two layers affect the performance of the IR system. In particular, it is affected by three main factors: The number of STAs (n) in the network, the FER or SNR of the IR channel and the window size (N). GBN efficiency improves compared to SW when N takes relatively high values and P_E is not extremely high ($P_E < 10^{-2}$). However, when n increases, larger windows must be used in order to achieve the same performance for the same P_E. These are somehow known results [12, 13. 19, 20, 21,] but the important issue is when and under which constraints GBN or SW performance is better taking into account the complex behavior of the 802.11 IR PHY and MAC layers. This is clearly answered by our analysis. Moreover, our analysis estimates N, n where the performance factor U equals one. These points are valuable in the case that a full adaptive ARQ scheme is employed over 802.11 MAC protocol. In such case the system could dynamically exchange the ARQ scheme used (choose either SW or GBN) by taking into account the measured FER, the window size N and the number of stations n. The implementation of a dynamic ARQ scheme based on our study will guarantee a decrease of the average packet delay and improvement of the quality of the offered service.

Note that the analysis is suitable without any significant modification for the general case of 802.11 optical links (802.11 standard assumes only IR) even for the case of a visible light communication system over 802.11. For example, instead of the IR LEDs it would be possible to use the newly white LEDs, which provide lighting of the indoor space and communication services [22].

If radio links are used, the situation is somewhat different. Modifications are required such as the extraction of the FER and the replacement of the IR MIB parameters with those of the radio.

Our analysis can be extended in order to relate U directly with the required transmitting power under specific channel conditions (irradiance of ambient light, possible interference by artificial light, distance from the transmitter) in order to achieve a certain SNR in the receiver. The latter extension is out of the scope of this paper and probably will be considered in a future communication, however, it is worthwhile to mention some problems involved in this extension. In general, the modeling of the diffused infrared channel is not really an easy issue. Some theoretical models exist [6, 23, 24, 25] but they are only applicable in simplified systems. On the other hand, experimental results cannot actually be reused since they strongly depend on the channel conditions, architecture of the indoor environment, the presence of furniture, the link design and the techniques applied for the transmission or reception of the IR signal [7, 24, 26, 27]. Thus, an implementation of an IR system will not be identical with that of another IR system and as a result, the mapping between U and the transmitted power will be valid only for the specific implementation.

Future considerations must also address the study of the more complicated by means of implementation, Selective Repeat ARQ scheme over the IR physical layer, comparison with the presented results of this paper and extensive study of a fully adaptive ARQ scheme.

9. CONCLUSIONS

We compared the well-known SW acknowledgement mechanism of 802.11 MAC protocol with the enhanced BurstAck scheme of the 802.11e MAC protocol, utilized as a GBN ARQ scheme with sliding window. The network uses the EDCF access method of 802.11e with the same parameters as the standard DCF. A finite number of STAs is assumed to transmit a number of MPDUs with fixed size for two cases. In the first case, all the STAs use the SW acknowledgment scheme, while in the second case they use the BurstAck scheme utilized as GBN with sliding window. Results of the compared channel efficiency are provided for various link parameters such as, the window size of the transmitted MPDUs, the number of

STAs, the FER and the SNR of the IR transmitted pulse. Those indicate that the utilization of BurstAck improves the channel performance under certain conditions. In general, for small window sizes $N \cong 10$, medium sized networks $n \cong 20$ and FER > 10^{-2} the performance of GBN is nearly the same or worse than SW and its implementation must be avoided. For larger window sizes, FER < 10^{-2} and networks with $n \leq 20$ the channel efficiency for GBN is better compared to SW.

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