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# Packet delay analysis of the advanced infrared (AIr) CSMA/CA MAC protocol in optical wireless LANs

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SUMMARY

During the past few years the wireless technology market has experienced a tremendous growth. Users today expect to be able to communicate and access data anytime, anywhere, using almost any portable device. Infrared Data Association (IrDA) addressed the requirement for indoor multipoint wireless connectivity with the development of the advanced infrared (AIr) protocol stack utilizing the infrared spectrum. AIr medium access control (MAC) protocol employs a carrier sensing multiple access with collision avoidance (CSMA/CA) protocol in addition to a request to send/clear to send (RTS/CTS) packet exchange reservation scheme and a linear adjustment of the contention window (CW). This paper develops a new modelling approach to evaluate saturation performance of the AIr protocol based on conditional probability arguments rather than bi-dimensional Markov chains. Moreover, we extend performance studies in former literature papers by providing an intuitive AIr packet delay analysis assuming error-free transmissions and a fixed number of stations. Using OPNET simulation results, we validate our mathematical analysis and we show that the proposed model predicts AIr packet delay performance very accurately. Utilizing the derived mathematical analysis, we determine the significance of both link layer and physical parameters, such as burst size, minimum CW size value and minimum turnaround time on AIr packet delay performance. Finally, we propose suitable values for both backoff and protocol parameters that reduce average packet delay and, thus, maximize performance. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: wireless LANs; CSMA/CA; optical wireless; IrDA; packet delay; performance evaluation

## 1. INTRODUCTION

Recent advances in technology have made it possible to include computing and networking technology into many devices such as mobile phones, laptop computers, printers, digital cameras or PDAs. A large number of new devices (over 40 million) are manufactured every year employing infrared ports in order to fulfil their wireless connectivity needs [1]. Furthermore, the

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growing number of laptop computers in the market today leads to an increasing demand for freedom from wired networks and for wireless LAN connectivity [2]. Infrared Data Association (IrDA) was established in 1993 by an industry-based group of over 150 leading companies aiming to develop and promote communication standards especially suited for low cost, short range, cross-platform, point-to-point communications at a wide range of speeds. The well-known IrDA 1.x platform architecture [3] provided half-duplex, line of sight links at data rates up to 16 Mbit/s [4]. The IrDA standards have been implemented on various computer platforms and became widely available on personal computers and peripherals.

The directed nature of the infrared link and the function of the IrDA 1.x protocol mean that only one pair of devices can be connected at a time and multiplexing must be on an application basis only. To deal with the increasing wireless LAN connectivity need and to overcome several IrDA 1.x protocol limitations, such as point-to-point and range restrictions, IrDA proposed a new standard for indoor wireless LANs called advanced infrared (AIr). The idea of the AIr protocol is to allow a pool of wireless users to share the infrared medium by employing a suitable medium access control (MAC) protocol. This is achieved by lifting the restrictions existed in the IrDA 1.x physical layer; IrLAP, the IrDA 1.x data link layer [5], is divided into three sub-layers consisting of the AIr-MAC layer [6], which controls access to the medium and avoids packet collisions, the AIr link management (AIr-LM) layer [7], which provides multiplexing for different client protocols and the AIr link control (AIr-LC) layer [8], which provides reliable data transfer and supports connections between multiple devices.

The new introduced physical layer, AIr PHY [9], is developed employing line of sight infrared ports operating at a wide-angle of $\pm 60^\circ$ [1, 10]. AIr PHY uses a four-slot pulse position modulation with variable repetition encoding (4PPM/VR) format with a base data rate of 4 Mbit/s. Transmission rate varies from 256 kbit/s to 4 Mbit/s, trading speed for range. Variable repetition encoding introduces redundancy used to improve signal-to-noise (SNR) ratio; better SNR provides additional transmission range [11, 12]. Long-range AIr transceivers provide an effective range of 3.8 m at 4 Mbit/s and an effective range greater than 7.6 m at 256 kbit/s.

AIr MAC co-ordinates access to the infrared medium by employing carrier sense multiple access with collision avoidance (CSMA/CA) techniques. AIr MAC provides reliable and unreliable transfer modes as well as unreserved and reserved media access. In reserved media access, a contending station reserves the infrared channel by using a request to send/clear to send (RTS/CTS) packet exchange and transmits a burst of data packets. The RTS/CTS exchange using the robust header of AIr packets effectively deals with the 'hidden node' problem common in wireless networks [13]. AIr MAC defines a long collision avoidance slot (CAS) time period ($\sigma$) that includes the beginning of the CTS packet to avoid collisions caused from stations hidden from the transmitter that are not able to receive the RTS packet. Collision avoidance procedures are employed in an effort to minimize collisions; a contending station first selects a number of CAS to defer transmission before attempting to reserve the media. This number is randomly selected in the range $[0, W-1]$, where $W$ is the current contention window (CW) size. Each station adjusts its current CW value based on the experienced collisions and successful reservations according to a linear CW adjustment. The AIr MAC protocol acts in a very similar manner to that of the IEEE 802.11 WLAN protocol [14] but with certain significant dissimilarities. The two main differences are that: (a) IEEE 802.11 utilizes a short time slot in contrast with AIr that makes use of a long CAS slot and (b) in IEEE 802.11 an exponential backoff is employed and not a linear one as in AIr. The performance of the 802.11 MAC has been analysed by various authors using both simulation [15] and analytical methods [16–19].

 

Although several papers in the literature [20–23] have attempted to study the AIr performance, none deals with the delay of a transmitted packet using the AIr protocol. In fact, the throughput performance of AIr MAC's unreserved transfer mode is presented in Reference [20] by using simulation techniques. Performance evaluation of reserved transfer modes by simulation is examined in Reference [21] and the fair access of the infrared medium by all contending stations is presented in Reference [22]. An analytical model utilizing a bi-dimensional Markov chain is derived in Reference [23] to calculate AIr throughput performance of unreserved and reserved transfer modes.

This paper presents an alternative and simpler derivation of the AIr performance analysis previously based on a bi-dimensional Markov chain model. The new derivation is based on elementary conditional probability arguments and is more elegant than the original one in Reference [23], since it clearly separates the backoff stage updating process from the backoff counter update [19]; the new approach can be applied to any CSMA/CA MAC protocol. We also extend the performance analysis presented in Reference [23] to calculate the average packet delay for the AIr protocol by deriving simple mathematical equations. As in Reference [23], the key approximation of our model is the assumption that a reservation attempt collides with a constant probability, which is independent of the number of collisions and successful reservations the station has experienced in the past.[¶] By comparing analytical with simulation results we present evidence that our model provides extremely accurate results for AIr packet delay performance. Utilizing the proposed analysis, we present an extensive AIr packet delay evaluation by taking into account all the factors and parameters that affect protocol performance. Finally, we propose suitable values for both backoff and protocol parameters that reduce average packet delay and, thus, maximize performance.

The rest of the paper is organized as follows. Section 2 provides an overview of the AIr MAC focusing on the collision avoidance procedures of the protocol. Section 3 presents the assumptions and protocol parameters utilized in our analysis. Moreover, a mathematical analysis is developed in order to compute the RTS packet collision and transmission probabilities as well as to calculate the average delay performance of packets being transmitted by the AIr protocol. Section 4 validates the proposed analysis by comparing analytical outcome with OPNET simulation results. Section 5 employs the derived mathematical analysis and provides an extensive performance evaluation of AIr MAC by studying the influence of the backoff and system parameters on protocol performance. Finally, Section 6 concludes the paper.

## 2. OVERVIEW OF AIR-MAC PROTOCOL

The variable repetition rate (RR) values that are supported by AIr PHY and MAC layers are presented in Table I. The receiver monitors channel quality and advises the transmitter to implement a suitable RR. The transmitter repeats the symbols it transmits RR times to increase the symbol capture probability at the receiver side. RR coding is very suitable for PPM that AIr protocol utilizes. A higher RR is used to achieve a better SNR [11, 12] as well as to reach a station that is far away from the transmitter (by trading speed for range).

[¶] An analytical model based on the same assumptions for the exponential backoff adjustment algorithm of the IEEE 802.11 protocol is presented in References [16–19].

Table I. AIr repetition rate (RR) values.

| RR | Data rate |
|---|---|
| 1 | 4 Mbit/s |
| 2 | 2 Mbit/s |
| 4 | 1 Mbit/s |
| 8 | 512 Kbit/s |
| 16 | 256 Kbit/s |

Table II. AIr MAC packet format types.

| Type | Description |
|---|---|
| RTS | Request to send (reservation) |
| CTS | Clear to send (reservation) |
| SOD | Start of data (reservation) |
| EOB | End of burst (reservation) |
| EOBC | End of burst confirmed (reservation) |
| UDATA | Unreserved data packet (data transfer) |
| DATA | Reserved data packet (data transfer) |
| SDATA | Reserved data packet with sequencing (data transfer) |
| ADATA | Reserved data packet with acknowledgment (data transfer) |
| ACK | Acknowledgment packet (data transfer) |
| SPOLL | Sequenced poll packet (data transfer) |
| SACK | Sequenced acknowledgment (data transfer) |

AIr MAC utilizes 12 packet types in total, which are given in Table II. Two general classes are defined; the reservation control packets (used to contend, initiate and terminate reservations) and the data transfer packets (used to transfer payload data). Figure 1 illustrates the general format of AIr packet. The Preamble (PA) field is transmitted for carrier sensing, symbol clock synchronization and chip clock phase acquisition by the phase locked loop (PLL). The synchronization (SYNC) field qualifies the carrier detection and allows exact identification of the beginning of the robust header element. Both PA and SYNC fields actually allow the receiver to detect the beginning of an incoming packet. The robust header (RH) field contains AIr PHY and AIr MAC information and is always transmitted using the maximum allowable RR encoding ($RR = 16$) to provide maximum detection sensitivity. Thus, all stations capable of interfering with the current transmission refrain from transmitting. The main body (MBR) field contains upper layer and AIr MAC information and is transmitted using variable RR shown in Table I. MBR contains payload data and has a variable length. PA, SYNC and RH fields are present in all AIr MAC packet types. MBR is not present in some packet types; in this case the RH field is not protected by a CRC because it is transmitted using maximum $RR = 16$. When present, it is followed by a cyclic redundancy check (CRC) field protecting both the RH and MB fields. The transmitter decides the suitable RR for specific transmission according to its evaluation the link quality to the receiving station. A receiving station also recommends RR values to the transmitter based on its evaluation of link quality.

AIr MAC defines reliable and unreliable data transfer modes as well as reserved and unreserved media access shown in Figure 2. Unreliable transfer modes (Figures 2(a) and 2(b)) guarantee the transmission of user data but not the delivery as no acknowledgement is provided

 

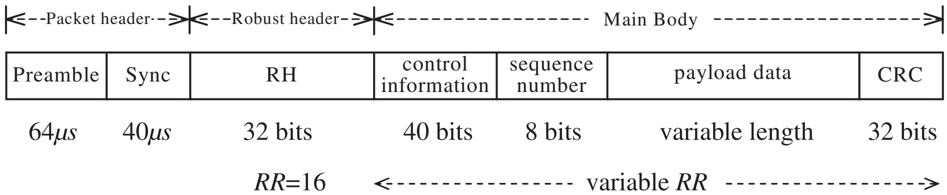


Figure 1. AIr general packet format.

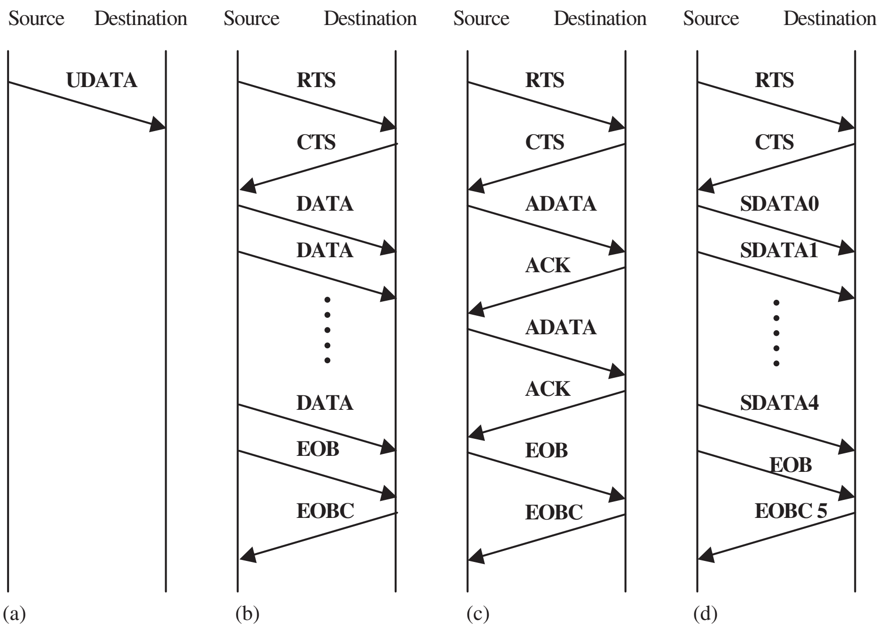


Figure 2. AIr MAC transfer modes: (a) unreserved transfer mode with UDATA packet; (b) reserved transfer mode with DATA packet (no acknowledgement); (c) reserved transfer mode with packet acknowledgement (ADATA packet); and (d) reserved transfer mode with sequenced data (SDATA packet).

to indicate correct packet reception. Reliable modes guarantee correct packet reception as an acknowledgement is provided for every data packet (Figure 2(c)) or for a packet burst (Figure 2(d)). Unreserved data transfer mode (Figure 2(a)) transmits only one UDATA data packet to a multicast or broadcast (i.e. all devices) address using $RR = 16$ to ensure maximum coverage. Note that the unreserved mode incurs the least overhead since does not reserve the infrared medium by employing the RTS/CTS packet exchange and is unreliable because no acknowledgment is received. Reserved transfer mode with no acknowledgement (Figure 2(b)) uses the RTS/CTS reservation scheme to reserve the medium, transmits a window of DATA packets in a successful reservation, terminates the reservation using the EOB/EOBC packet exchange but it is still unreliable since no acknowledgement is exchanged. When one of the above two data transfer modes is used, a MAC successful transmission indication to LM layer means that the packets are sent and not that the packets are correctly received. Reserved transfer mode with acknowledgement (Figure 2(c)) and reserved transfer mode with sequenced data (Figure 2(d)) also employ the RTS/CTS reservation scheme and successful data reception is based on an immediate acknowledgement packet (ACK) and on a receiver's indication in the end of burst confirm (EOBC) packet of the next packet expected, respectively. For these two data transfer modes, a MAC successful transmission indication to LM layer means that the packets are correctly received. Since this work studies the performance of the reserved access reliable sequenced transfer mode (SDATA), the format definition of the AIr MAC packets used in SDATA is shown in Figure 3.

In reservation media access schemes (Figures 2(b)–2(d)), the transmitting station reserves the medium for the duration contained in the reservation time (RT) field of the RTS packet it transmits. After a turn around time (TAT) delay, the receiving station responds with a CTS packet and echoes the reservation period in the RT field of the CTS packet. As the RT field is contained in RH, it is always transmitted using maximum $RR = 16$ to ensure maximum coverage. Thus, even stations being able to hear only the RTS or only the CTS packet defer transmission for the entire reservation period. Moreover, the RTS/CTS scheme is employed to address the hidden station (a station not being able to hear the transmitter or the receiver) problem [13] at the expense of the time required for transmitting the RTS and CTS packets. When the transmitter receives the CTS packet, waits for a TAT delay and initiates a window packet transmission. After the last data packet is transmitted and before the reservation time expires, the transmitter requests termination of current reservation by transmitting an end of

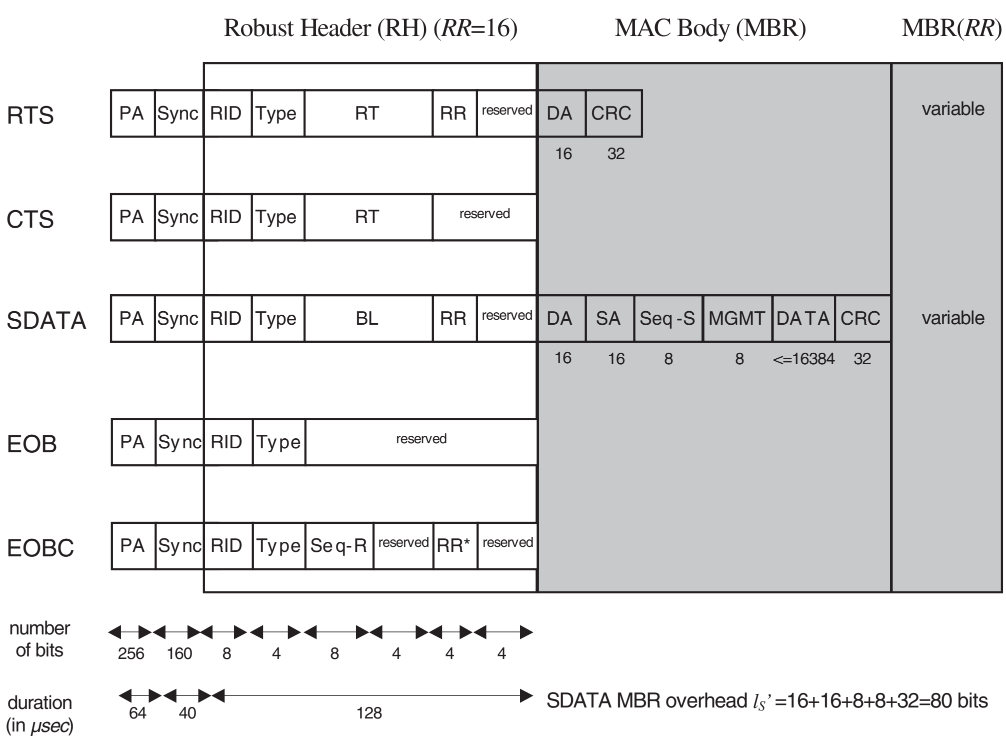


Figure 3. AIr MAC packet definitions.

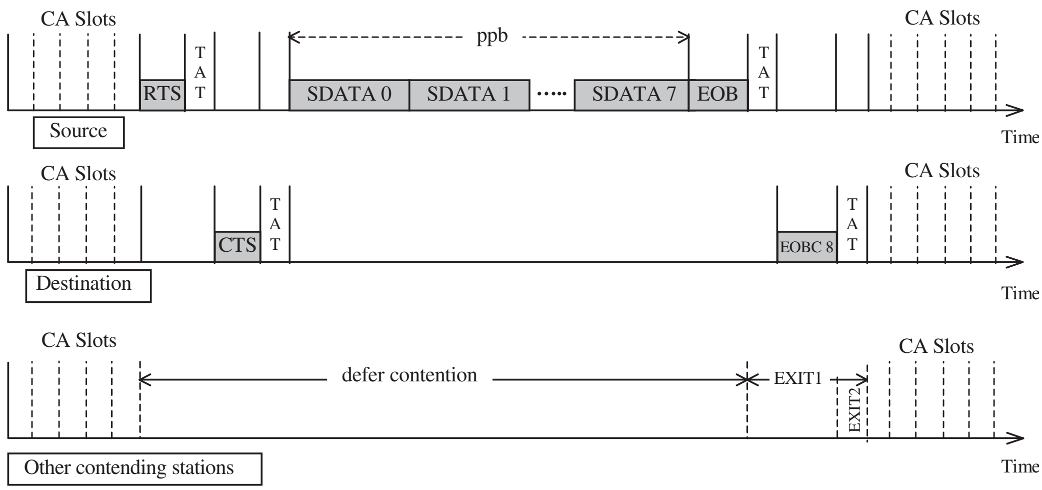


Figure 4. Reserved access scheme with sequenced transfer mode (SDATA packets).

burst (EOB) packet. The receiver waits a TAT period and confirms termination of current reservation by responding with an EOBC packet. As with RTS/CTS exchange, a station receiving the EOBC or the EOB packet realizes that the current reservation is over and that it is able to contend for the medium again.

AIr MAC employs CSMA/CA techniques to minimize collision probability. A station wishing to transmit and regardless of the transfer mode it employs, it first invokes the CA procedures in an effort to minimize collisions with other stations. In the SDATA transfer mode, which is presented with detail in Figure 4, a contending station always invokes the CA procedures before an RTS packet transmission. The contention period is slotted and a station is allowed to transmit only at the beginning of each slot time ($\sigma$). A competing station for medium access first senses the medium; if the medium is busy, it waits for the transmitting station to finish and for the beginning of the next contention period. The contending station then initializes its backoff counter by selecting an integer random number of CAS to defer transmission in order to minimize the collision probability with other transmissions. This backoff counter is uniformly selected in the range $(0, \mathrm{CW}-1)$ where CW is the current contention window size and the backoff interval is assigned to CAS timer. The CW size values depend on the number of successful reservations and collisions that the transmitting station has experienced in the past. If during the station's deferral period another transmission is observed, the station freezes its CAS timer and restarts it again when the ongoing transmission is finished (the medium becomes free again) and the next contention period is started.[‖] When the CAS timer reaches zero, the station attempts to reserve the channel by transmitting an RTS packet. While a transmitter is sending a packet, it blinds its own receiver such that it cannot receive remote infrared pulses. The receiving station waits a minimum TAT to allow for the transmitter's receive circuitry to recover and responds with a CTS packet. After the successful

‖ Contention period starts a TAT period after the EOBC packet that terminates a reservation. The TAT delay is required because the station that transmitted the EOBC packet should be able to receive the next packet. Contention period ends when a non-colliding RTS packet is transmitted.

 

RTS/CTS exchange, the transmitting station, after a TAT delay, transmits a burst of data packets and requests termination of current reservation by transmitting a EOB packet. The receiving station responds with an EOBC packet confirming reservation termination. The reservation time duration is echoed in the RT field of both the RTS and CTS packets. Thus, stations being able to hear only the RTS or only the CTS packet refrain from transmitting for the entire reservation period.

AIr MAC also considers synchronizing all stations contending for the medium at exactly the same time after a successful RTS/CTS medium reservation, even for stations hearing only the EOB or the EOBC packet. Synchronization is accomplished by implementing two timers (EXIT1 and EXIT2). EXIT1 time duration is defined as the TAT after the EOB plus the transmission time of the EOBC packet plus the TAT after the EOBC packet and EXIT2 is defined as the TAT delay (Figure 4). Moreover, a contending station, after transmitting the RTS packet, starts the wait for CTS (WFCTS) timer. If another (one or more) stations has selected the same CAS slot, it transmits an RTS packet at the same time and the reservation attempt is unsuccessful. The transmitting stations determine the resulting collision by the WFCTS timer expiration. This timer value ($\geqslant \mathrm{TAT} + \mathrm{TT}_{\mathrm{RH}}$) expresses the amount of time a station that has transmitted an RTS packet will wait for the corresponding CTS packet. If a valid CTS has not been received within the WFCTS period, the transmitter assumes that a collision occurred and contends again for medium access by selecting a new CAS slot and re-attempting a reservation. To synchronize the colliding stations with the remaining stations, the WFCTS timer should expire at the end of the current time slot. Time required for transmitting packets and packet elements as well as the timer values used in our work are summarized in Table III.

The AIr protocol defines a CAS duration, which is significantly longer than the one of similar CSMA/CA protocols in order to provide an effective solution to utilization degradation caused by collisions from hidden stations, a problem which is likely to appear in infrared LANs. For example, the IEEE 802.11 specification [14] defines that the CAS duration accounts for the propagation delay, for the time needed to switch from receiving to transmitting state and for the time needed for the physical layer to signal the channel state to the MAC layer. In AIr MAC,

Table III. AIr timer durations, packet and packet element transmission times for $C = 4$ Mbit/s.

| Packet/packet element | Duration | Time (μs) |
|---|---|---|
| $T_{\mathrm{PA}}$ (packet element) | | 64 |
| $T_{\mathrm{SYNC}}$ (packet element) | | 40 |
| $T_{\mathrm{RH}}$ (packet element) | | 128 |
| $TT_{\mathrm{RH}}$ (packet) | $T_{\mathrm{PA}} + T_{\mathrm{SYNC}} + T_{\mathrm{RH}}$ | 232 |
| $T_{\mathrm{RTS}}$ (packet) | $TT_{\mathrm{RH}} + 48/C$ | 244 |
| $T_{\mathrm{CTS}}$ (packet) | $TT_{\mathrm{RH}}$ | 232 |
| $T_{\mathrm{EOB}}$ (packet) | $TT_{\mathrm{RH}}$ | 232 |
| $T_{\mathrm{EOBC}}$ (packet) | $TT_{\mathrm{RH}}$ | 232 |
| $T_{\mathrm{ACK}}$ (packet) | $TT_{\mathrm{RH}}$ | 232 |
| TAT | | 200 |
| $\sigma$ (CAS slot) | | 800 |
| EXIT1 timer | $\mathrm{TAT} + T_{\mathrm{EOBC}} + \mathrm{TAT}$ | 632 |
| EXIT2 timer | TAT | 200 |
| WFCTS timer | $\sigma - T_{\mathrm{RTS}}$ | 556 |

the CAS duration ($\sigma$) is defined as being greater than the transmission time of the RTS packet plus the TAT delay plus the time need to detect the beginning portion (PA and SYNC fields) of the responding CTS packet ($\sigma > T_{\mathrm{RTS}} + \mathrm{TAT} + TT_{\mathrm{PA}} + TT_{\mathrm{SYNC}}$). Such a long CAS duration ensures that contending stations hidden from the transmitter that are not able to hear the RTS packet transmission but not from the receiver will receive the beginning of the CTS packet within a single CAS duration. Thus, a longer CAS duration provides a much better hidden station approach at the expense of possible performance degradation if the number of empty and colliding CAS during the contention periods is high. This number depends on the number of the competing stations and on the CW values used by these stations.

As stations can only adjust their CW values after successful reservations and collisions, the implemented CW adjustment algorithm becomes of great importance if maximum utilization is to be achieved. Small CW size values result in a very high collision probability and, therefore, to low performance due to the increased number of collisions. When large CW size values are implemented, the increased number of empty CAS will also result in low medium utilization. A station can only estimate the suitable CW value it should implement based on the experienced successful reservations and collisions. AIr specifications define that the AIr-LM layer selects the CW value to be used in every reservation attempt and pass it down to the MAC layer. The AIr-LM layer does not provide rules for CW size adjustment but suggests guidelines by utilizing a linear algorithm for incrementing and decrementing CW after a collision and a successful reservation attempt, respectively. This CW size adjustment can be achieved since the transmitting station always 'remembers' the CW value used in the previous reservation attempt. If this attempt was successful, CW is decreased by 4; if it resulted in a collision, CW is increased by 4. A minimum CW value of 8 (lower limit) and a maximum CW value of 256 (upper limit) are also defined [7].

## 3. MATHEMATICAL ANALYSIS AND MODELLING

Our mathematical analysis consists of three parts. The first part presents the assumptions and the parameters that we utilize in our analysis. The second part considers the behaviour of a single station to compute the conditional probability $p$ that an RTS packet experiences a collision and the stationary probability $\tau$ that a station transmits an RTS packet in a randomly chosen CAS for a network of $n$ stations. Note that both probabilities are independent of the reserved access scheme employed by the stations. Finally, in the last part, by examining the events that can occur in a randomly chosen CAS, we derive the average delay performance of packets being transmitted by the AIr protocol; simple equations calculate packet delay as a function of probabilities $p$ and $\tau$. The key assumption used in our model is that an RTS transmission always collides with probability $p$ regardless of the CW value used to select the deferral period for the reservation attempt.

### *3.1. Analysis assumptions and parameter definitions*

This work concentrates on the packet delay performance for a fixed number of stations under saturation conditions. In saturation conditions, every station has immediately a burst of packets ready for transmission, after the completion of each successful burst transmission. In other words, the transmission queue for every station is always non-empty. All burst of packets are considered 'consecutive', each one needs to wait for a random backoff time before being transmitted. All stations always employ the reserved transfer mode with sequenced data although the analytical model can be easily altered to evaluate performance of the remaining reserved transfer modes supported by the AIr MAC (Figure 2). After a successful reservation attempt, a station transmits packets per burst (ppb) of fixed payload size of $l$ bits at a fixed data rate of $C$ Mbit/s. We assume ideal channel conditions meaning that a non-colliding packet is always received error-free to all network stations. Current analysis also assumes that reservation control packets (RTS, CTS, EOB and EOBC) are always transmitted error-free. This is a realistic assumption because, since control packets CTS, EOB and EOBC contain only an RH portion which is transmitted using the maximum repetition rate $\mathrm{RR} = 16$ to minimize transmission errors. An RTS control packet has also an MBR field consisting of only 48 bits, which is transmitted using variable RR. This MBR length is extremely small for the expected link quality and the assumption that the RTS packets are always transmitted error-free also holds true. Moreover, since we do not consider channel bit errors, an RR increase resulting in higher symbol capture probability at the receiver is not considered. The MB of all data packets are always transmitted in the same RR and the RH portion is transmitted in the protocol suggested RR value of 16. We also assume that the one-way propagation delay is very small and can be safely neglected due to the fact that the considered indoor links operate at very short distances. Moreover, our analysis also assumes that there are no hidden stations. Thus, all stations will always receive the RTS and the CTS packets of a successful reservation. Therefore, there is no fairness problem as all stations have an equal chance to reserve the infrared medium.

### 3.2. *Calculation of the RTS transmission probability*

As explained earlier, the backoff counter for every station depends on the collisions and on the successful reservation attempts experienced by the station in the past. The CSMA/CA protocol procedure specifies that before transmitting each station selects a random value for its backoff counter in the range $(0, W - 1)$. If the reservation attempt failed (the RTS transmission collided), then the AIr protocol employs the linear backoff i.e. the next backoff value will be selected in the range $[0, (W + 4) - 1]$ and so forth. We define for convenience $W = \mathrm{CW}_{\min}$. Let $m$ be the 'maximum backoff stage' defined as $\mathrm{CW}_{\max} = W + 4m$. Since a station may be in stage $i \in [0, m]$, we adopt the following notation:

$$W_i = W + 4i, \quad i \in (0, m) \tag{1}$$

where $i$ is defined as the backoff stage that identifies the number of retransmissions suffered by an RTS packet. According to the definition, we have $W = W_0 = \mathrm{CW}_{\min}$ and $W_m = \mathrm{CW}_{\max}$. AIr standard specifies that $\mathrm{CW}_{\max} = 256$ and $m = 62$ [7].

Let us denote with TX the event that a station is transmitting during a slot time and with $P(s = i|\mathrm{TX})$ the steady-state probability that a transmitting station is found in stage $i > 0$. Since this probability is given by the probability that the station, in the previous transmission slot, was found in stage $i - 1$ and that the transmission failed (with probability $p$), it follows that $P(s = i|\mathrm{TX})$ can be calculated as

$$P(s = i|\mathrm{TX}) = c\left(\frac{p}{1 - p}\right)^i \tag{2}$$

where $c$ is a constant parameter that we will derive next and $p$ is the probability that a reservation attempt fails due to a collision, when at least one of the $n-1$ remaining stations transmit an RTS packet in the same time slot. If we assume that all stations see the system at steady state and transmit with probability $\tau$, the collision probability $p$ is given by

$$p = 1 - (1-\tau)^{n-1} \tag{3}$$

For convenience in further calculations, we set

$$a = \frac{p}{1-p} \tag{4}$$

Since a station is always found in the $i$ stage, we have

$$\sum_{i=0}^{m} P(s=i|\text{TX}) = 1 \tag{5}$$

Substituting (2) and (4) into (5), the value of the parameter $c$ is found as

$$c = \frac{1-a}{1-a^{m+1}} = \frac{1-p/1-p}{1-(p/1-p)^{m+1}} \tag{6}$$

Using (4) and (6), (2) becomes:

$$P(s=i|\text{TX}) = \frac{(1-2p)(1-p)^m}{(1-p)^{m+1}-p^{m+1}}\left(\frac{p}{1-p}\right)^i \tag{7}$$

We are ultimately interested in the unconditional probability $\tau = P(\text{TX})$ that the station transmits a packet in a randomly chosen slot. By utilizing Bayes' theorem:

$$P(s=i|\text{TX}) = \frac{P(\text{TX}|s=i)P(s=i)}{P(\text{TX})} \tag{8}$$

which in turn yields, for all $i$ values in $(0,\ldots,m)$:

$$P(\text{TX})\frac{P(s=i|\text{TX})}{P(\text{TX}|s=i)} = P(s=i) \tag{9}$$

This equality yields also for the summation:

$$P(\text{TX})\sum_{i=0}^{m}\frac{P(s=i|\text{TX})}{P(\text{TX}|s=i)} = \sum_{i=0}^{m} P(s=i) = 1 \tag{10}$$

A reservation attempt occurs when the backoff counter of the transmitting station becomes equal to zero, regardless of the backoff stage. Thus, the transmission probability $\tau$ is equal to

$$\tau = P(\text{TX}) = \frac{1}{\sum_{i=0}^{m}\dfrac{P(s=i|\text{TX})}{P(\text{TX}|s=i)}} \tag{11}$$

It remains to find an expression for the conditional probability $P(\text{TX}|s=i)$. This probability can be calculated by dividing the average number of slots a station spends in the transmission state $(i,0)$ while in stage $i$ (exactly 1 slot according to the adopted time scale), and the average number of slots that a station spends in the backoff stage $i$ which is equal to $(W_i+1)/2$. Since the average number of slot times spent for each backoff counter transition is exactly 1 slot,

 

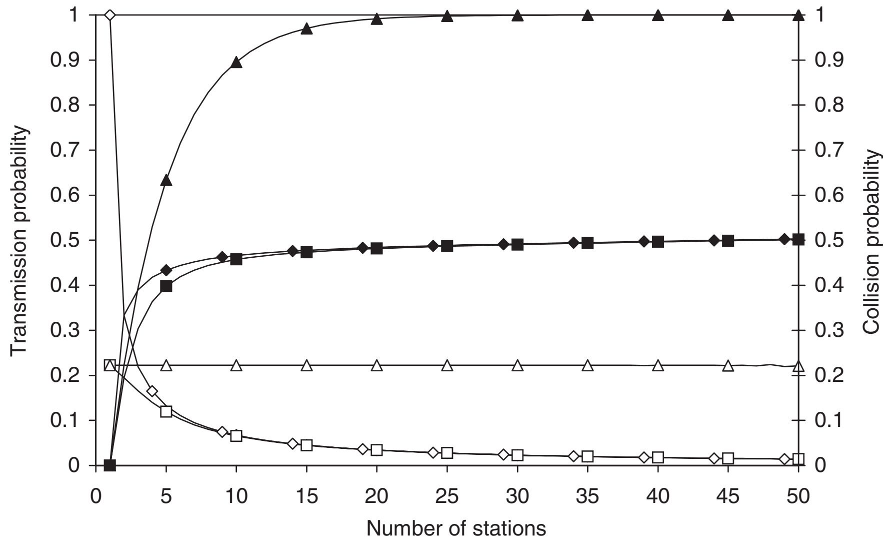


Figure 5. RTS packet collision and transmission probabilities, $l = 16$ kbits, ppb = 1. ▲: collision probability, CW = 8, $m = 0$; △: transmission probability, CW = 8, $m = 0$; ■: collision probability, CW = 8, $m = 62$; □: transmission probability, CW = 8, $m = 62$; ◆: collision probability, CW = 1, $m = 62$; ◇: transmission probability, CW = 1, $m = 62$.

therefore:

$$P(\mathrm{TX}|s = i) = \frac{1}{1 + 1(W_i - 1)/2} = \frac{2}{W_i + 1} \tag{12}$$

Therefore, the probability $\tau$ that a station transmits a packet in a randomly chosen slot time is equal to

$$\tau = \frac{1}{\sum_{i=0}^{m} \left[\frac{(1-2p)(1-p)^m}{(1-p)^{m+1}-p^{m+1}} \left(\frac{p}{1-p}\right)^i \frac{W_i+1}{2}\right]} = \frac{2}{\frac{(1-2p)(1-p)^m}{(1-p)^{m+1}-p^{m+1}} \sum_{i=0}^{m} \left[\left(\frac{p}{1-p}\right)^i (W_i + 1)\right]} \tag{13}$$

After some algebra, Equation (12) becomes equal to**

$$\tau(p) : \tau = \frac{2}{(W + 1) + \frac{4p((1-p)^{m+1} + (2m+1)p^{m+1} - (m+1)p^m)}{((1-p)^{m+1} - p^{m+1})(1-2p)}} \tag{14}$$

Equations (3) and (14) represent a non-linear system with two unknowns $p$ and $\tau$. This system can be solved by utilizing numerical methods and evaluating $p$ and $\tau$ for a certain $W$ and $m$ combination. Note that $p \in [0, 1]$ and $\tau \in [0, 1]$. As it has been shown in Reference [23] throughout a detailed proof, this non-linear system has a unique solution.

Figure 5 shows how the RTS packet collision and transmission probabilities, $p$ and $\tau$, respectively, are affected from the network size and the various backoff parameters. This figure plots both probabilities as a function of the number of stations $n$ and for different CW and $m$

**Note that the above expression for the probability $\tau$ is consistent with the one found in Reference [23] but not with the one in References [17] or [18] for the IEEE 802.11 exponential backoff algorithm. From Equation (14), we observe that the transmission probability $\tau$ depends on the collision probability $p$.

 

values. When no CW size adjustment is enforced after a successful reservation or collision ($m = 0$), the figure illustrates that the collision probability is highly dependent on the number of stations. A large network size results in a higher collision probability and, thus, in an increased number of collisions. Conversely, when $m = 0$ the probability of an RTS transmission is practically not affected by network size. If CW size is increased or decreased after a collision or a successful reservation, respectively, results show that the collision probability increases as network size increases for $n < 20$. Moreover, the RTS transmission probability is decreased for $n$ values less than 25; for larger network size scenarios $\tau$ attains roughly the same values having a slight decreasing trend.

### 3.3. *Packet delay analysis*

This section presents an elegant method to calculate the average packet delay for a successfully transmitted packet, based on the analysis derived in the previous section. The average delay $E[D]$ is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until its successful reception. The average packet delay $E[D]$ can be found by

$$E[D] = E[X]E[\text{slot}] \tag{15}$$

where $E[X]$ is the average number of time slots needed for a successful packet transmission and $E[\text{slot}]$ is the average length of a slot time. $E[X]$ is calculated as

$$E[X] = \frac{1}{\tau(1-p)\text{ppb}} = \frac{1}{\tau(1-\tau)^{n-1}\text{ppb}} \tag{16}$$

From Equation (15) we observe that the average packet delay depends on the average length of a slot time $E[\text{slot}]$ which is still unknown and will be calculated next. Based on the calculated RTS collision probability $p$ and transmission probability $\tau$, and in order to compute $E[\text{slot}]$, we now analyse all possible events that can occur in a randomly chosen time slot. Let $P_{\text{tr}}$ be the probability that at least one reservation attempt occurs (at least one station transmits an RTS packet) in the considered slot. For a LAN of $n$ stations, each transmitting with probability $\tau$, $P_{\text{tr}}$ is given by

$$P_{\text{tr}} = 1 - (1-\tau)^n \tag{17}$$

A packet collision takes place when two or more contending stations initiate simultaneously an RTS packet transmission attempting to reserve the infrared medium in the same slot time. The conditional probability $P_{\text{s}}$ that an occurring RTS transmission is successful is given by the probability that exactly one station transmits and the remaining $n-1$ stations defer transmission, conditioned on the fact that at least one station (out of $n$ stations) transmits an RTS packet.

$$P_{\text{s}} = \frac{P_{\text{success}}}{P_{\text{tr}}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{18}$$

Therefore, a successful reservation attempt in a randomly selected slot occurs with probability $P_{\text{tr}}P_{\text{s}}$ and the time utilized for transmitting payload information is ppb $t$, where ppb is the window size and $t$ is defined as the time required for transmitting payload information data in an SDATA packet. The value of $t$ is given by

$$t = \frac{l}{C} \tag{19}$$

where $l$ is the packet payload data length and $C$ is the data rate.

The average slot duration can be evaluated by considering that a random slot is empty with probability $1 - P_{tr}$, with probability $P_{tr}P_s$ the slot contains a successful reservation and with probability $P_{tr}(1 - P_s)$ the slot contains a collision. Thus, the average length of a slot time $E[\text{slot}]$ is equal to

$$E[\text{slot}] = (1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c \tag{20}$$

where $\sigma$ is the duration of an empty slot time, $T_s$ and $T_c$ are the time durations the medium is sensed busy due to a successful reservation and a collision involving two or more simultaneous packet transmissions, respectively. A collision always lasts exactly one CAS and, therefore:

$$T_c = \sigma \tag{21}$$

Considering Equation (21), Equation (20) can be easily reduced to

$$E[\text{slot}] = P_{tr}P_sT_s + \sigma - P_{tr}P_s\sigma \tag{22}$$

For AIr networks employing the reserved transfer mode with sequenced data (SDATA packet) (Figure 2(d)), the duration of $T_s$ is equal to

$$T_S^{\text{SDATA}} = D_{\text{over}} + \text{ppb}(t + F_S + p_1) \tag{23}$$

where $D_{\text{over}}$ is the reservation overhead that includes the transmission time of the RTS, CTS, EOB and EOBC packets as well as the TAT delays that follow these packets, $F_S$ is the transmission time of the SDATA packet overhead (preamble, robust header, CRC, etc.) and $p_1$ is the preparation time of an SDATA packet (practically equal to zero). Assuming that the RTS MBR field is always transmitted using RR = 1, $D_{\text{over}}$ is given by

$$D_{\text{over}} = T_{\text{RTS}} + \text{TAT} + T_{\text{CTS}} + \text{TAT} + T_{\text{EOB}} + \text{TAT} + T_{\text{EOBC}} + \text{TAT} \tag{24}$$

The value of $F_S$ can be found as

$$F_S = TT_{\text{RH}} + \frac{\text{RR}\, l'_S}{C} \tag{25}$$

where $l'_S$ is the length of the MBR overhead of an SDATA packet and $T_{\text{RH}}$ is the transmission time of a packet with no MBR field (defined in Section 2). Table III gives all the packet and packet element transmission times for $C = 4$ Mbit/s. Finally, if we substitute Equations (16) and (22) into Equation (15), the average packet delay $E[D]$ can be easily calculated.

Our analytical model also allows measurement of the time portion utilized on all component tasks affecting AIr delay performance. Such an evaluation reveals the impact of physical and link layer parameters to utilization. It is valuable for link designers in achieving high utilization at a reasonable cost and for link implementers in selecting suitable parameter values in order to maximize performance. Considering that a randomly selected slot is empty with probability $1 - P_{tr}$ and that the CAS duration is $\sigma$, the time portion utilized in empty CAS because no station transmits is given by

$$T_{\text{empty}} = \frac{(1 - P_{tr})\sigma}{P_{tr}P_sT_s + \sigma - P_{tr}P_s\sigma} \tag{26}$$

 

A randomly selected slot contains a collision with probability $P_{tr}(1 - P_s)$ and the time portion utilized on collisions when two or more stations are simultaneously trying to reserve the infrared channel is

$$T_{coll} = \frac{P_{tr}(1 - P_s)\sigma}{P_{tr} P_s T_s + \sigma - P_{tr} P_s \sigma} \tag{27}$$

The time portion utilized on transmitting data packet overheads, the control packets (RTS/CTS/EOB/EOBC) and the associated TAT delays during a successful reservation period is given by

$$T_{over} = \frac{P_{tr} P_s (T_s - l\text{ppb}/C)}{P_{tr} P_s T_s + \sigma - P_{tr} P_s \sigma} \tag{28}$$

As all component tasks that affect AIr delay performance are considered, the following equation always holds true:

$$T_{empty} + T_{coll} + T_{over} + U = 1 \tag{29}$$

where $U$ is defined as the utilization (throughput efficiency) of the link that can be found in Reference [23]. Equation (29) can be easily verified from Equations (26), (27) and (28).

## 4. MODEL VALIDATION

In this section, we validate the previously presented analytical model by comparing analytical with simulation results obtained using the AIr simulator introduced in Reference [21]. This simulator was developed using the OPNET modeller modelling and simulation software package [24] and closely follows all timer values and packet element transmission times defined by AIr specifications. OPNET modeller is an event-driven simulator and provides a powerful graphical tool to display simulation statistics. OPNET uses hierarchically linked domains to denote a network design and stations are defined in the network domain, which is the top-level domain. Each station has a set of processes and each process can represent a layer in the protocol stack. Moreover, a process can be defined by a finite state machine. The transmission of packets across network links is controlled by pipeline-stage $C/C^{++}$ coded routines and the user can produce and add C code to be executed when entering and exiting each state. In fact, our OPNET AIr simulator emulates the real operation of a wireless station as close as possible, by implementing the collision avoidance procedures and by closely following all parameters such as TATs, propagation delays and packet transmission times defined by AIr specifications.

In fact, we have suitably modified the standard library of OPNET in order to employ saturation conditions, i.e. all stations always have a packet ready for transmission. After the essential modification of the simulator in order to calculate AIr packet delay performance, we have run simulations on network sizes varying from 1 to 50 stations, in steps of 5. In all simulation runs, we assumed ideal channel conditions; an error-free medium is assumed and no hidden stations are considered. Furthermore, the reserved transfer mode with sequenced data was employed; stations transmit ppb SDATA packets in every successful reservation attempt. Each SDATA packet is always carrying 16 kbits of payload data (the maximum allowable size) at the 4 Mbit/s data rate.

 

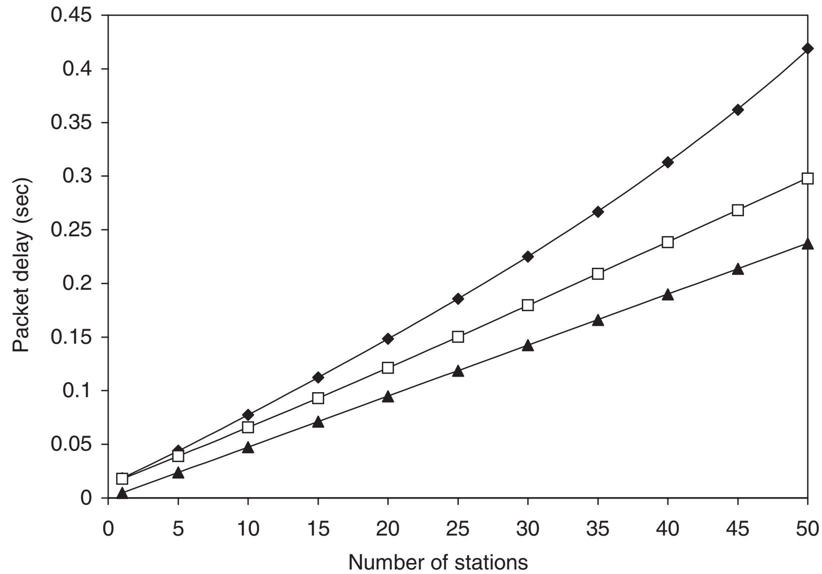


Figure 6. Packet delay: analysis (lines) versus simulation (symbols), $l = 16$ kbits, $C = 4$ Mbit/s. ◆: CW = 32, $m = 4$, ppb = 1; □: CW = 64, $m = 62$, ppb = 2; ▲: CW = 8, $m = 62$, ppb = 8.

Figure 6 provides packet delay performance results versus the number of stations and studies the accuracy of the developed mathematical analysis. The parameters used in both the analytical model and the simulation runs follow the parameters summarized in Table III. The performance comparison shows that analytical results (lines) coincide with simulation results (symbols) for different $W$, $m$ and ppb values. Note that simulation results are acquired with a 95% confidence interval lower than 0.002. Our packet delay analysis gives results in high agreement with OPNET simulations and, therefore, it predicts very accurately AIr packet delay performance. Furthermore, an interesting observation is that packet delay significantly depends on the implemented backoff parameters such as $W$, $m$ and ppb. The presented performance results are a strong indication of the great importance for the proper selection of the backoff and protocol parameters in order to reduce packet delay and, thus, maximize performance.

## 5. PERFORMANCE EVALUATION

This section studies the impact of the backoff and system parameters on AIr MAC protocol performance by employing the previously derived mathematical analysis. Figure 7 explores the dependency of performance on the CW size. Packet delay results are plotted versus number of stations when no CW size adjustment is imposed ($m = 0$) after a successful reservation or collision. The figure shows that packet delay is not practically affected when a large CW size is implemented (CW = 32 or 64) for any network scenario. Conversely, when a lower CW size is being used, packet delay is highly dependent on the network size $n$. When $n$ increases, the increased number of collisions results in high packet delay values and, therefore, in significant performance degradation, especially for small CW size values. Thus, for a given network size

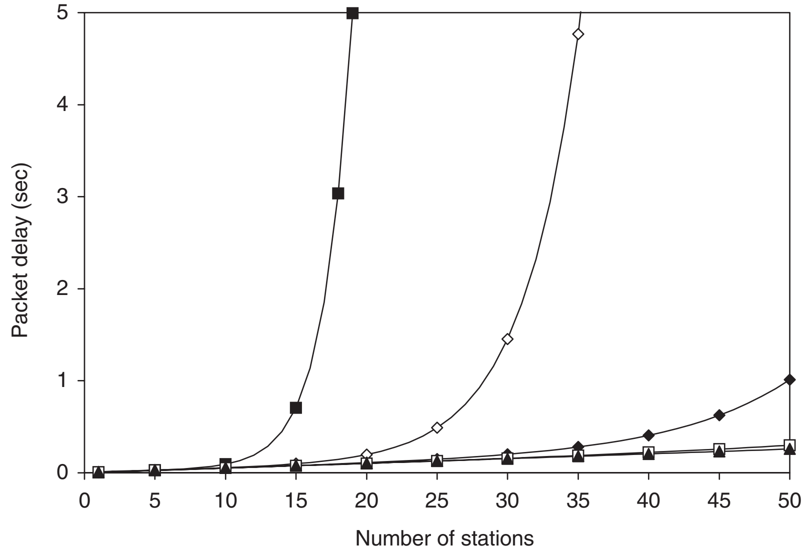


Figure 7. Packet delay versus $n$ for fixed CW size, $l = 16$ kbits, ppb = 4. ■: CW(slots) = 4; ◇: CW(slots) = 8; ◆: CW(slots) = 16; □: CW(slots) = 32; ▲: CW(slots) = 64.

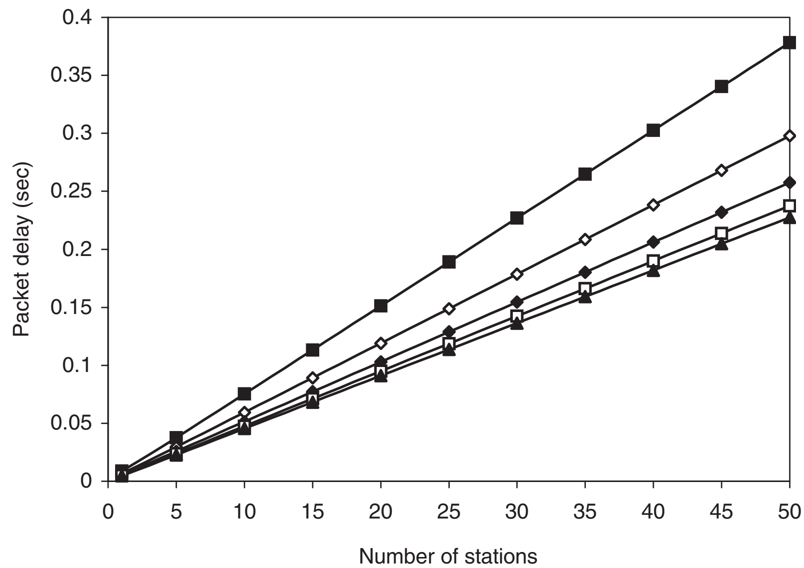


Figure 8. Packet delay versus $n$, for various ppb values, $l = 16$ kbits, CW = 8, $m = 62$. ■: ppb = 1; ◇: ppb = 2; ◆: ppb = 4; □: ppb = 8; ▲: ppb = 16.

and when no CW size adjustment is implemented, an appropriate CW size value should be chosen in order to obtain minimum packet delay and as a result maximum performance.

The effect of the number of ppb on performance is examined in Figure 8 by plotting packet delay versus network size for different ppb values (ppb = 1, 2, 4, 8 and 16). Results show that performance is significantly improved by putting multiple packets, and not only one, into each burst transmission. The situation is justified by noting that for each packet transmission a separate set of overhead information and delays (reservation time, inter-frame spaces, backoff time and acknowledgements) is needed. With packet bursting, instead of several sets of overhead for each packet, only one set of overhead information will be used. In this way, the packet delay can be reduced and the performance is significantly improved. Another useful observation is that the performance is not considerably enhanced when ppb = 16 compared to the case of ppb = 8.

Figures 9 and 10 clearly show all the factors affecting packet delay versus network size for two different ppb values (ppb = 1 or 16). Figure 9 plots throughput efficiency and the time portion utilized on empty slots. The figure depicts that when the number of ppb is either equal to 8 or 16 instead of ppb = 1, throughput efficiency of the communication is increased. Note that when ppb = 1, only 55% of the time is devoted in useful transmission in contrast with the case of ppb = 8 or 16 when the equivalent amount of time is 82–88%. Furthermore, high ppb values significantly decrease the amount of time consumed on empty slots. Figure 10 plots the time portion utilized in packet collisions and in transmitting overheads during a successful transmission i.e. SDATA packet headers, and control packets such as RTS, CTS, EOB and EOBC. The figure shows that when ppb increases, the amount of time consumed on inadequate tasks like packet collisions or transmitting overheads is significantly reduced. Thus, high ppb values appear to be a necessity in improving performance.

The effectiveness of the proposed CW size adjustment mechanism and $CW_{max}$ value is explored in Figures 11 and 12. These figures plots packet delay versus CW size and maximum backoff stage $m$, respectively, for 5 different network sizes ($n$ = 1, 5, 10, 20 and 50). Both figures show that the network size affects the performance considerably; in large networks packet delay

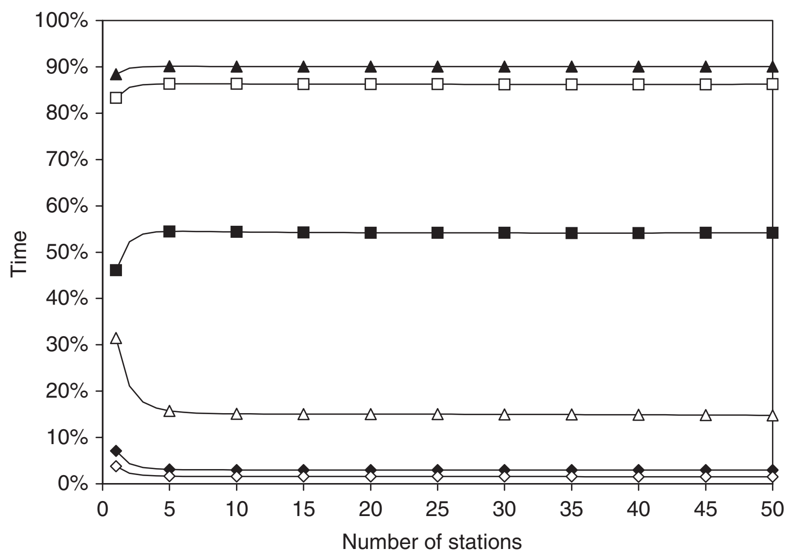


Figure 9. Time allocation of various AIr tasks versus $n$, $l = 16$ kbits, CW = 8, $m = 62$. ■: throughput efficiency, ppb = 1; □: throughput efficiency, ppb = 8; ▲: throughput efficiency, ppb = 16; △: empty slots, ppb = 1; ◆: empty slots, ppb = 8; △: empty slots, ppb = 16.

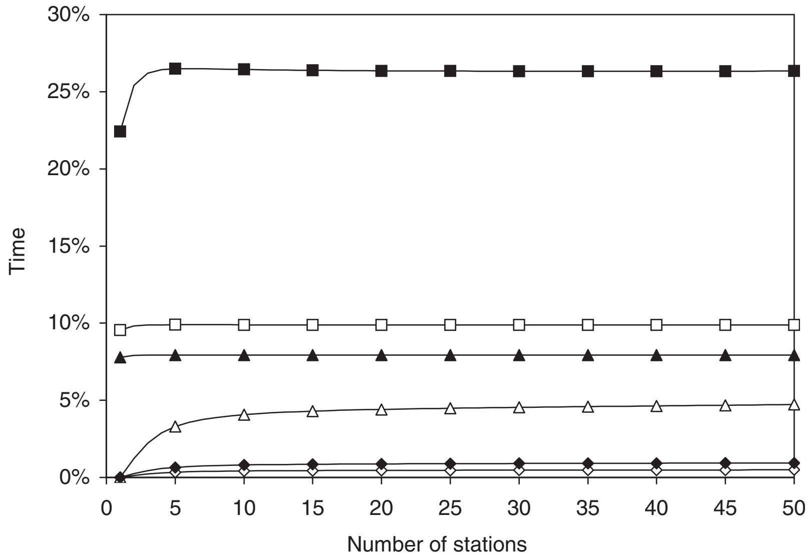


Figure 10. Time allocation of various AIr tasks versus $n$, $l = 16$ kbits, CW = 8, $m = 62$. ■: transmitting overheads, ppb = 1; □; transmitting overheads, ppb = 8; ▲: transmitting overheads, ppb = 16; △: collisions, ppb = 1; ◆: collisions, ppb = 8; ◇: collisions, ppb = 16.

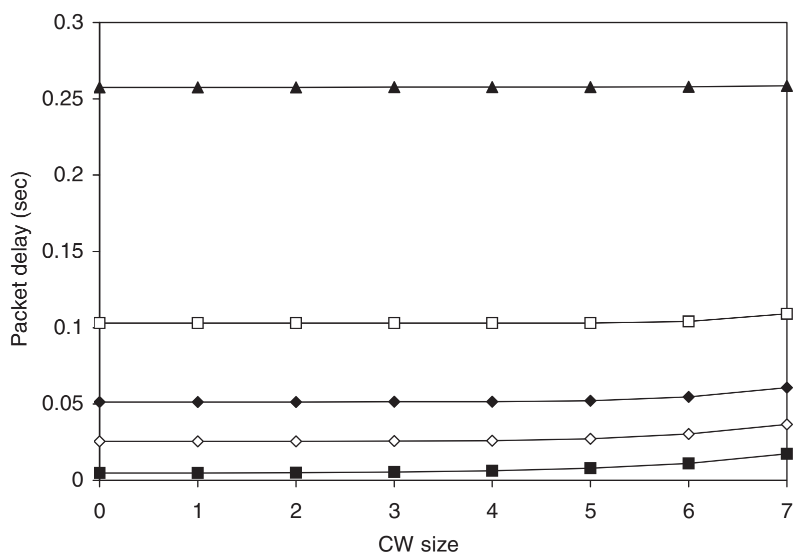


Figure 11. Packet delay versus CW size, for various $n$ values, $l = 16$ kbits, CW = 8, $m = 62$, ppb = 4. ■: $n = 1$; ◇: $n = 5$; ◆: $n = 10$; □: $n = 20$; ▲: $n = 50$.

attains higher values than smaller networks due to the increased number of collisions no matter the CW size or the maximum backoff stage. Figure 11 depicts that the choice of CW size does not practically affect packet delay when a CW size adjustment mechanism exists ($m = 62$),

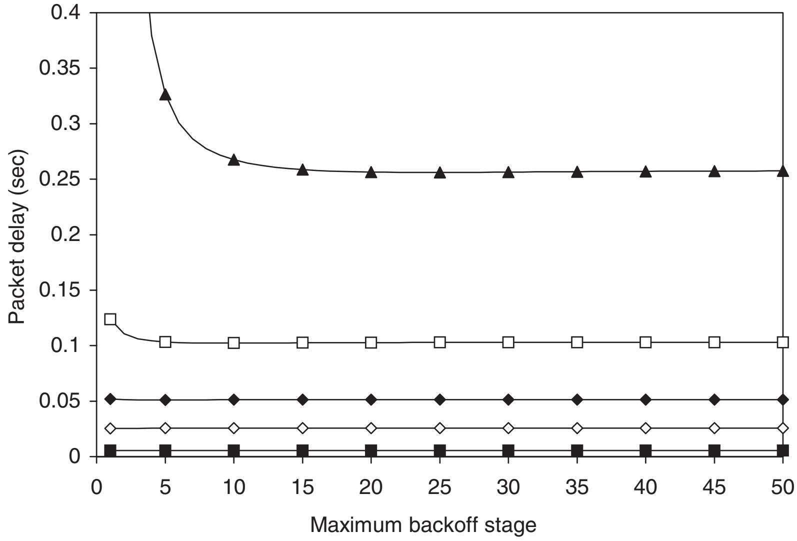


Figure 12. Packet delay versus $m$, for various $n$ values, $l = 16$ kbits, CW = 8, ppb = 4. ■: $n = 1$; ◇: $n = 5$; ◆: $n = 10$; □: $n = 20$; ▲: $n = 50$.

especially for high values of $n$. This conclusion is significantly different to the expressed conclusion in Figure 7 that an appropriate CW size value is essential for maximum performance.

Figure 12 examines the appropriateness of the $CW_{max}$ value selected in the AIr standard. In the case of large network sizes, the choice of $m$ plays a key role in reducing packet delay; small $m$ values result in a significant high packet delay and, therefore, impair performance. Moreover, performance results show that the dependence of the packet delay from the maximum backoff stage $m$ for small networks is marginal. However, the figure illustrates that packet delay and, therefore, performance is not practically affected when the maximum backoff stage $m$ is greater than 20. This means that a $CW_{max}$ value of 64 instead of the proposed value of 256 is sufficient enough for maximum performance. This result can be explained as follows. Since AIr utilizes a linear adjustment of the CW size and the CW is increased by 4 (a relatively small value) after a packet collision. For this reason, large $CW_{max}$ values are rarely used and only after a large number of consecutive packet collisions. As a result, $CW_{max}$ can be safely lowered even for large network sizes.

Figure 13 investigates the dependency of performance on various physical layer parameters by plotting packet delay against network size. The figure reports packet delay for the case of transmitting the RH field of all packets using RR = 1 (instead of RR = 16) for scenarios in which only one data packet of 16 kbits (ppb = 1) is transmitted as well as for lower minimum TAT and CAS slot size ($\sigma$) values. Note that the implemented CAS slot time has to obey the restriction that $\sigma > T_{RTS} + \mathrm{TAT} + TT_{PA} + TT_{SYNC}$ in order to ensure that a station not hearing the RTS control packet will hear the beginning of the CTS control packet during the CAS time duration and defer transmission. The set of values utilized to derive Figure 13 are displayed in Table IV. As we can observe packet delay is considerably decreased if the RH field of all packets is transmitted using RR = 1. Moreover, performance is also improved by appropriately reducing the minimum TAT and the CAS slot size. Therefore, the lowest packet delay values are

 

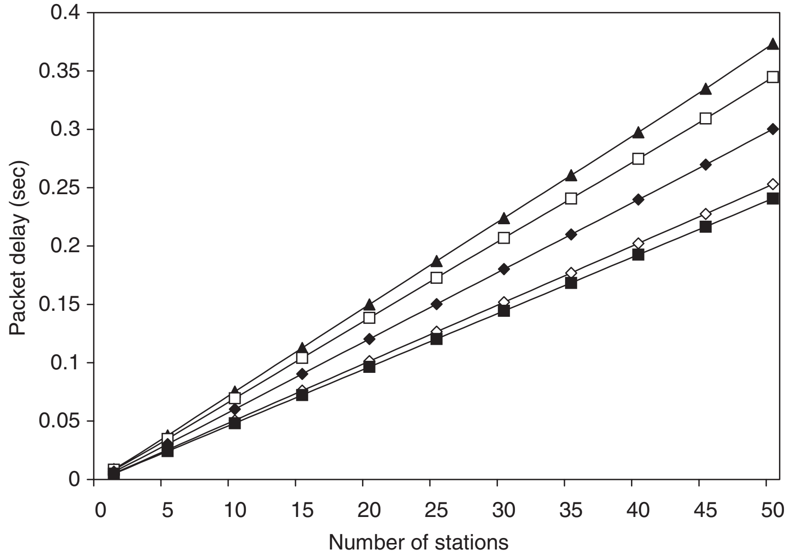


Figure 13. Packet delay versus $n$, for various physical layer parameters, $l = 16$ kbits, CW = 8, $m = 20$. ■: RR = 1, $\sigma = 50$, TAT = 10, ppb = 1; ◇: RR = 1, $\sigma = 100$, TAT = 50, ppb = 1; ◆: RR = 1, $\sigma = 300$, TAT = 200, ppb = 1; □: RR = 16, $\sigma = 700$, TAT = 100, ppb = 1; ▲: RR = 16, $\sigma = 800$, TAT = 200, ppb = 1.

Table IV. AIr physical and link layer parameters for improved performance.

| | RR | | | | |
|---|---|---|---|---|---|
| Parameter | 16 | 16 | 1 | 1 | 1 |
| TAT | 200 | 100 | 200 | 50 | 10 |
| $T_{RTS} + TAT + T_{PA} + T_{SYNC}$ | 548 | 448 | 428 | 278 | 238 |
| CAS duration ($\sigma$) | 800 | 700 | 300 | 100 | 50 |
| $F_s$ | 252 | 252 | 132 | 132 | 132 |
| $D$ | 1740 | 1340 | 1260 | 660 | 500 |

achieved for RR = 1 and for the much smaller than the proposed TAT and $\sigma$ values (TAT = 10, $\sigma = 50$).

In Figures 14 and 15 we clearly demonstrate why performance is considerably improved when the RH field of all packets is transmitted using RR = 1 and when smaller values TAT and $\sigma$ values are implemented. These figures plot throughput efficiency and the time portion utilized on empty slots (Figure 14) and the time portion utilized in packet collisions and in transmitting overheads during a successful transmission (Figure 15). Figure 14 shows that performance is significantly enhanced when RH is transmitted in RR = 1 and for lower TAT and $\sigma$ values since more time is utilized for useful transmission and less time is consumed in empty slots. Figure 15 also confirms the previous conclusion since much less time is utilized in transmitting overheads or in packet collisions.

In Figure 16, packet delay is plotted against packet size in bits in order to study the effect of the packet payload size on performance. As it is expected, packet delay increases when packet

 

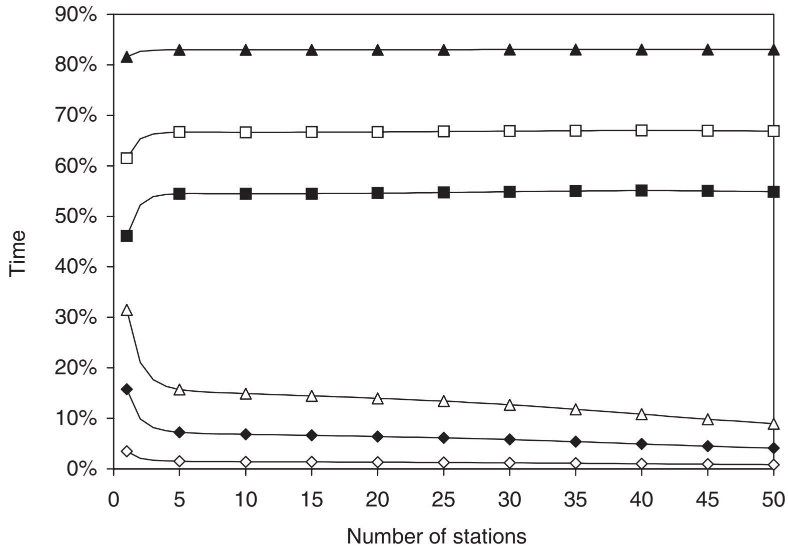


Figure 14. Time allocation of various AIr tasks versus $n$, $l = 16$ kbits, $W = 8$, $m = 20$, ppb $= 1$. ■: throughput efficiency, RH in RR = 16, $\sigma = 800$, TAT = 200; □: throughput efficiency, RH in RR = 1, $\sigma = 300$, TAT = 200; ▲: throughput efficiency, RH in RR = 1, $\sigma = 50$, TAT = 10; △: empty slots, RH in RR = 16, $\sigma = 800$, TAT = 200; ◆: empty slots, RH in RR = 1, $\sigma = 300$, TAT = 200; ◇: empty slots, RH in RR = 1, $\sigma = 50$, TAT = 10.

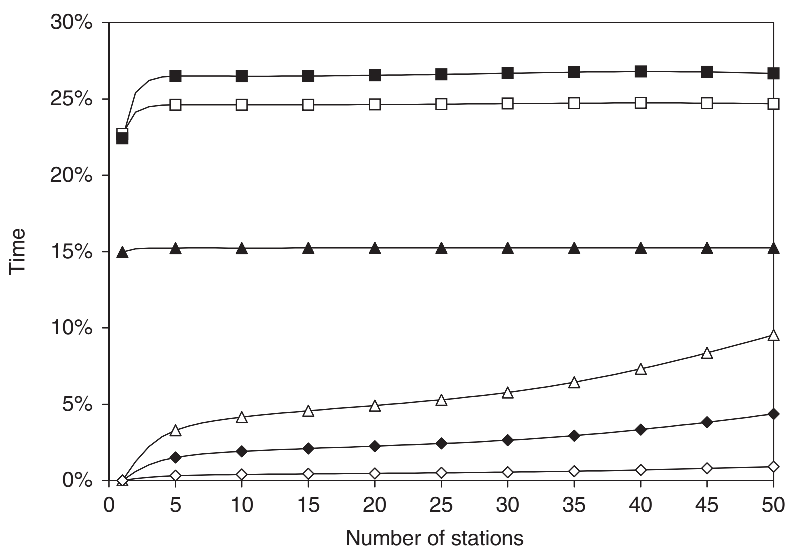


Figure 15. Time allocation of various AIr tasks versus $n$, $l = 16$ kbits, $W = 8$, $m = 20$, ppb $= 1$. ■: transmitting overheads, RH in RR = 16, $\sigma = 800$, TAT = 200; □: transmitting overheads, RH in RR = 1, $\sigma = 300$, TAT = 200; ▲: transmitting overheads, RH in RR = 1, $\sigma = 50$, TAT = 10; △: collisions, RH in RR = 16, $\sigma = 800$, TAT = 200; ◆: collisions, RH in RR = 1, $\sigma = 300$, TAT = 200; ◇: collisions, RH in RR = 1, $\sigma = 50$, TAT = 10.

 

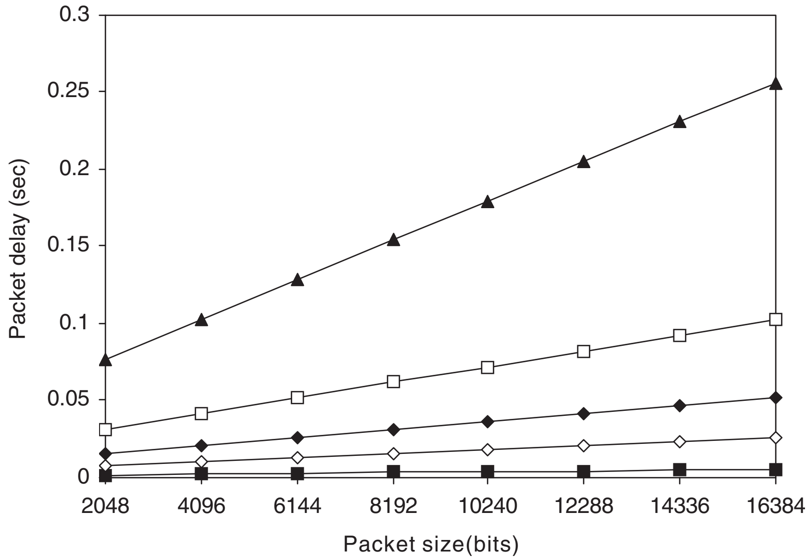


Figure 16. Packet delay versus $l$, for various $n$ values, $W = 8$, $m = 20$, ppb = 4. ■: $n = 1$; ◇: $n = 5$; ◆: $n = 10$; □: $n = 20$; ▲: $n = 50$.

size increases, especially in large network scenarios. However, it is understandable that throughput efficiency is improved when large-size packets are transmitted since in this way the negative effect on performance of the packet overhead is minimized. For this reason, we are opposite a trade-off between throughput efficiency and packet delay performance as the network size increases.

## 6. CONCLUSIONS

In this paper, we presented a new and simpler derivation of the performance model in Reference [23]. This new derivation is simpler than the original one and accurate since is validated by comparison with OPNET simulation results. Furthermore, a novel and intuitive analysis is derived that leads to simple equations for the average packet delay of the AIr protocol. Utilizing the proposed analysis, we present an extensive AIr packet delay evaluation by taking into account all the factors and parameters that affect protocol performance.

We observe that when no CW size adjustment is imposed ($m = 0$) after a successful reservation or collision, packet delay performance is significantly affected particularly for small network sizes; a suitable CW size value should be chosen for maximum performance. Moreover, results show that performance does not considerably depend on the maximum backoff stage for $m$ values greater than 20. Another important parameter that affects packet delay is the payload size of the transmitted data packets. Performance results point out that there is a trade-off between throughput efficiency and packet delay performance, especially when the network size increases. Finally, for indoor environments in which small amounts of data (ppb = 1) are transmitted in every successful reservation attempt, both the RR used in transmitting the RH field of all packets as well as the minimum TAT can be safely lowered in order to reduce packet delay and, thus, enhance the performance.

 

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